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FEASIBILITY OF HORIZONTAL BORING FOR SITE INVESTIGATION IN SOIL

February 1976

Final Report

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FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Washington, D. C. 20590

FOREWORD

This report contains the results of a research effort conducted by the Federal Highway Administration through the Massachusetts Institute of Technology to determine the feasibility of horizontal boring for site investigations in soil.

The report describes techniques, equipment, justification, and cost estimates for drilling horizontal holes in soft ground for site exploration purposes. The study was divided into three separate topics: excavation, exploration, and economics. The main objective of the study was to assess horizontal boring and exploration as an alternate to vertical boring in geotechnical investigations prior to the design and construction of tunnels.

Sufficient copies of the report are being distributed by FHWA Bulletin to provide a minimum of one copy to each FHWA Regional Office, one copy to each FHWA Division Office, and two copies to each State highway agency. Direct distribution is being made to the Division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

The objective of this study is to assess horizontal boring and exploration as an alternative to vertical boring in geotechnical investigation prior to the design and construction of tunnels. The study was divided into three separate topics: Excavation, Exploration, and Economics.

Under Excavation, new ideas and preliminary designs were developed for continuous, maneuverable penetration out to distances of 5000 ft (1500 m). Detailed methodology is presented for penetration to 2000 to 3000 ft (610 to 915 m) with recently developed equipment and technology.

Under Exploration, preliminary designs were developed for down-hole seismic (geophysical) and contact sensing. These approaches were technically evaluated by investigation of wave attenuation characteristics and hole disturbance.

Under Economics, horizontal penetration (with on-board sensing and separate follower sensing) was compared for cost effectiveness with vertical boring and surface geophysics. In addition, the cost of unanticipated conditions was summarized from case histories to assess the value of the various exploration approaches.

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The investigation was conducted in the Constructed Facilities Division of the Department of Civil Engineering at Massachusetts Institute of Technology. Dr. Charles H. Dowding, Assistant Professor of Civil Engineering, was the principal investigator.

Four consultant/subcontractors provided the industrial input necessary for the success of the project. Mr. Martin Cherrington, Mr. Myron Emery (now with Dyna-Drill), and Mr. Mike Preseau of Titan Contractors, Sacramento, California, provided experience and case histories of directional drilling and reviewed the finding concerning penetration. Raymond Harlan of the Charles Stark Draper Laboratory, Cambridge, Massachusetts, wrote the Appendix on Navigation Equipment for Horizontal Penetration. Vincent Murphy of Weston Geophysical Engineers, Westboro, Massachusetts, provided practical experience in geophyscial exploration and reviewed the findings concerning geophyscial exploration. Dr. Elizabeth Schumacher of the Civil Engineering Department at M.I.T. wrote the Appendix on Operating Costs of Mandrel and Thruster Systems and reviewed the findings concerning the cost and value analyses.

Four graduate students in the Civil Engineering Department at M.I.T. assisted in the research. Three of these students, Jan Hedberg (geophysical and contact sensing and hole stability), Lt. A. W. Katz (excavation/penetration) and Daniel Zielinski (Cerretos Channel crossing) wrote theses based upon findings during the course of the investigation. They, together with the fourth graduate student, Duane Labreche (cost analysis), gathered and helped synthesize the information upon which this report is based.

Six individuals were responsible for publication support during this project. Mr. Donald Goodell performed initial editing and Ms. Ruth Wagner "kept the books" and typed the progress reports. Ms. Elin Carboneau drafted the figures. A special thanks is extended to Ms. Jane Browning, who edited and typed the first draft of this report. Ms. Carole Beals and Ms. Rhonda Levinson typed the final draft.

Considerable assistance was obtained from correspondence and conversations with industrial and academic researchers and practitioners. The list of contributors appears as Appendix B in this report. The gracious assistance of the contributors is gratefully appreciated.

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CHAPTER 1

INTRODUCTION/EXECUTIVE SUMMARY

1.1 OBJECTIVES OF INVESTIGATION

Because of the potential savings in horizontal hole exploration for tunnels, the Department of Transportation has undertaken the development of horizontal penetration for exploration purposes. The initial stage of development was divided into two efforts: (1) "Drilling and Preparation of Reuseable, Long Range Horizontal Bore Holes in Rock and Gouge Materials," for development of horizontal excavation equipment for penetrating rock, and (2) "Determination of the Feasibility of Using Horizontal Penetration Techniques for Pre-excavation Subsurface Investigation in Soft Ground Transportation Tunnels," for development and economical justification for penetrating soil. This report presents the results of the second portion of the study.

The objectives of the investigation can be summarized under three main headings: Excavation, Exploration, and Economics. Under Excavation, new ideas and preliminary designs were developed for horizontal, continuous, maneuverable penetration. The equipment is targeted to operate below the water table and at distances of 0 to 5000 ft (0 to 1500 m). Detailed methodology is presented for penetration to 2000 to 3000 ft (610 to 915 m) with recently developed equipment and technology. Under Exploration, the technical feasibility of combining geophysical and contact sensing techniques with horizontal penetration was evaluated. The technical feasibility was determined through consideration of the physical laws governing the seismic wave attenuation, and the disturbance resulting from the penetration device. Under Economics, the operational and developmental costs of the excavation and exploration were investigated. In addition, the values of exploration by vertical and horizontal methods were determined to guide further planning.

The three objective areas of investigation are tabulated below by percent of effort. Note that Items 3 and 4 are economic in nature. Therefore, the study is divided evenly between Excavation, Exploration, and Economics. Resultant horizontal excavation and exploration technqiues and concepts will be summarized next. They will be followed by a summary systems' analysis of the alternatives and economic attributes. Conclusions and recommendations will then be given and the chapter will close with a discussion of the study's scope.

<u>PRINCIPAL CONTRACT OBJECTIVES</u>	<u>% EFFORT</u>
1. DEVELOP LONG DISTANCE MANEUVERABLE PENETRATORS/EXCAVATORS Penetration--Navigation--Guidance--Preliminary Design	35
2. COMBINE EXPLORATION WITH HORIZONTAL PENETRATORS Hole Stability--Contact Sensing--Geophysical Sensing	28
3. PROJECT COSTS--MANDREL AND THRUSTER SYSTEMS Titan--CONOCO--DRILCO Improvements Thereof	11
4. ANALYZE VALUE OF HORIZONTAL EXPLORATION Tunnel Savings--Exploration Efficiency--Scenarios	24
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1.2 THRUSTER AND MANDREL EXCAVATION/PENETRATION SYSTEMS

Two principal methods of developing normal force at the bit (mandrel and thruster) were investigated. Both of these methods can be combined with various downhole motors, bits, navigation, sensing and communication subsystems.

The mandrel system, developed by Titan Contractors, is pushed through the ground by the up-hole drill carriage, "Big Alice" shown in Figure 1.1 (up-hole normal force development). To date, Alice has been able to emplace 12 in. (30 cm) diameter product lines out to 700 ft (213 m) and 5 in. (13 cm) diameter product lines out to 1700 ft (518 m). The hole is drilled with a 1 3/4 in. Dyna-Drill downhole motor with a

BIG-ALICE - TITANS HORIZONTAL DRILLING RIG

DYNA-DRILL, BENT HOUSING W/PAD, WASHOVER

FIGURE 1.1
MANDREL SYSTEM - CONCEPT, FIELD DEPLOYMENT
(Photos courtesy of Titan Contractors)

bent housing and is cased with a 3 in. (8 cm) washover pipe. The drill steel connecting the motor to Alice does not rotate except to steer, as the bit is rotated by a downhole motor. Course changes are affected by changing the ratios of normal force/bit rotation and rotation of the eccentrically mounted bit and motor.

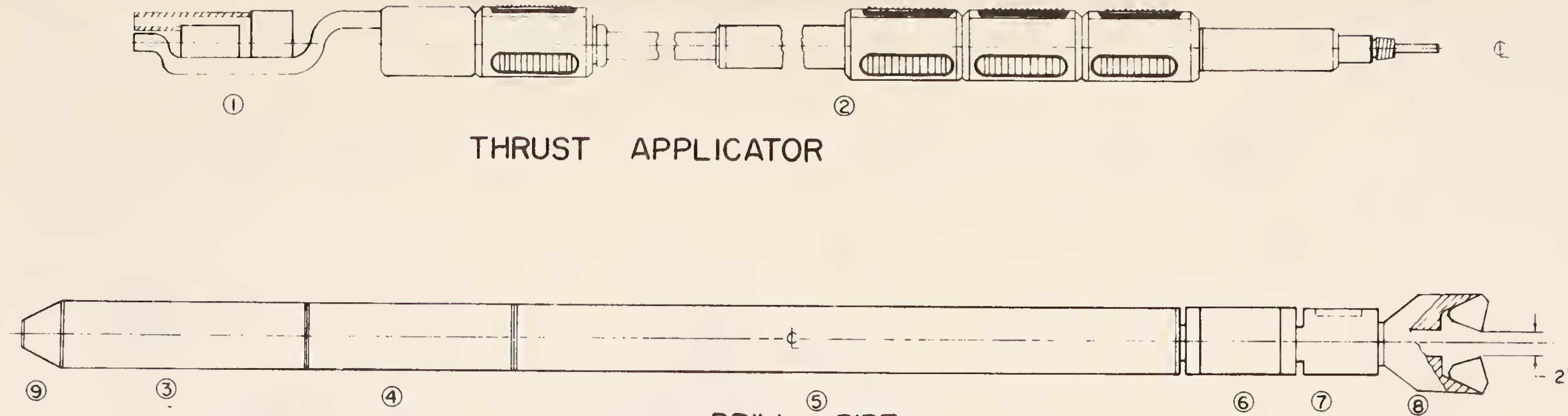
Titan's project histories show that pilot holes with the washover system are regularly made to 1400 to 1700 ft (430 to 518 m) and could be made an estimated maximum of 2000 to 3000 ft (610 to 915 m). Return of cuttings and hydraulic fracturing need improvement for significant increases in range. Appendix N, Cerritos Channel Crossing: A Detailed Operational Study, contains enough information of Titan Contractors' methodology to permit consideration of their technique by engineers.

The thruster system, developed by CONOCO and DRILCO Industrial, generates normal force by thrusting against anchors pressed against the hole and is connected to the surface with flexible cable. Course changes are made by deflecting jacks (shoes) near the bit. The details of the thrust applicator are shown in Figure 1.2. Field deployment during early testing of the thrust applicator is shown in Figure 1.3 along with the original conception of the system configuration. CONOCO has been able to repeatedly penetrate up to 800 ft (244 m) in soft coal. Bit wear, cuttings transport, hydraulic line loss and variable anchor pressure will need improvement for significant increases in range.

The thrust applicator, a basic component to the thruster system, is built in two models with 3 in. and 6 in. (7.6 cm and 15 cm) diameter. The single cylindered 3 in. (7.6 cm) diameter model can supply a bit thrust of 7000 lbs. Additional cylinders in series can increase thrust. The ability of the thruster system to penetrate in a given formation is a function of the bit's ability to cut at least a 3.5 in. (9 cm) hole with 7000 lbs. thrust and the anchor's ability to permit that thrust to be developed.

1.3 EXPLORATION APPROACHES

Soil parameters relevant to tunneling design can be divided into two major groups: geometry of the subsurface environment, and soil and



COMPONENTS: ATTACH TO DRILL PIPE (MANDREL) OR THRUSTER

The mandrel is a non-rotating drill pipe of smaller diameter than the hole. It transfers thrust from the uphole drilling platform to the illustrated downhole components, and is protected by the washover pipe. See page N-10 for the geometrical details of mandrel and washover pipe and N-2 and N-19 for the platform.

	COMPONENTS
①	Downhole hyd valving
②	Thrust applicator
③	Electronic package
④	Orientating motor
⑤	Hyd drill motor
⑥	Deflection Shoe
⑦	Bit sub
⑧	Tricone core bit
⑨	Bent sub

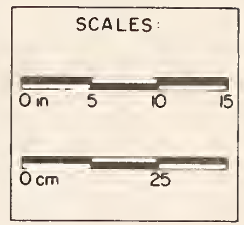
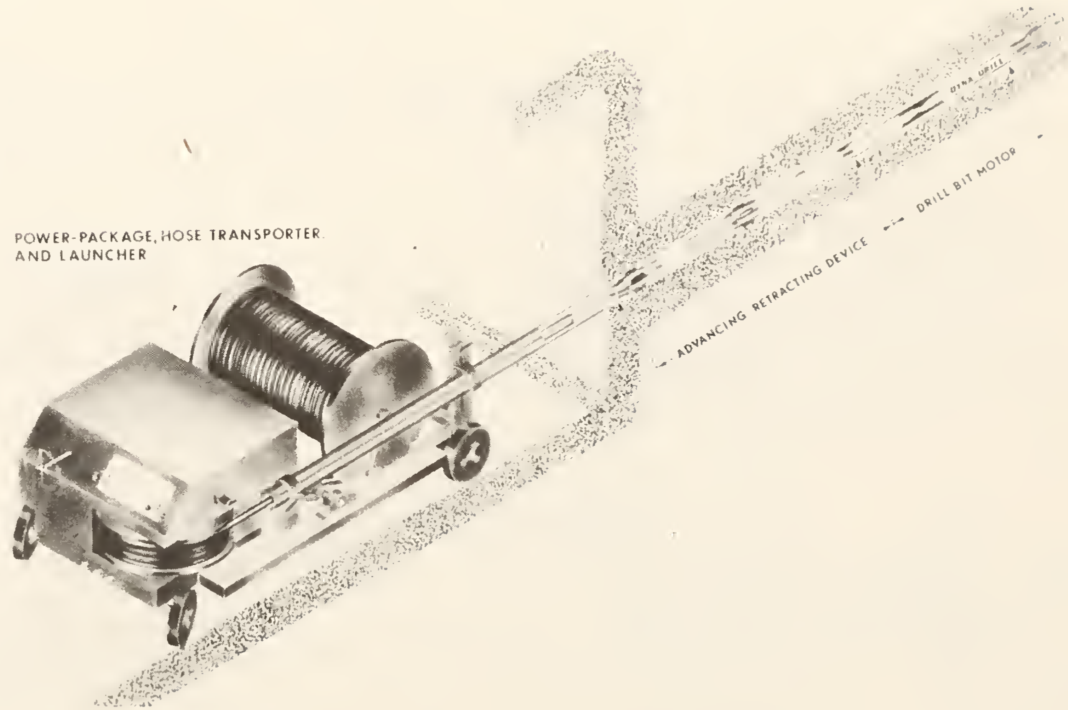


FIGURE 1.2 PROPOSED DOWNHOLE EQUIPMENT

FIELD DEPLOYMENT



POSSIBLE FUTURE SYSTEM DESIGN

FIGURE 1.3

THRUSTER SYSTEM - CONCEPT AND FIELD DEPLOYMENT
(PHOTOS COURTESY OF DRILCO INDUSTRIAL)

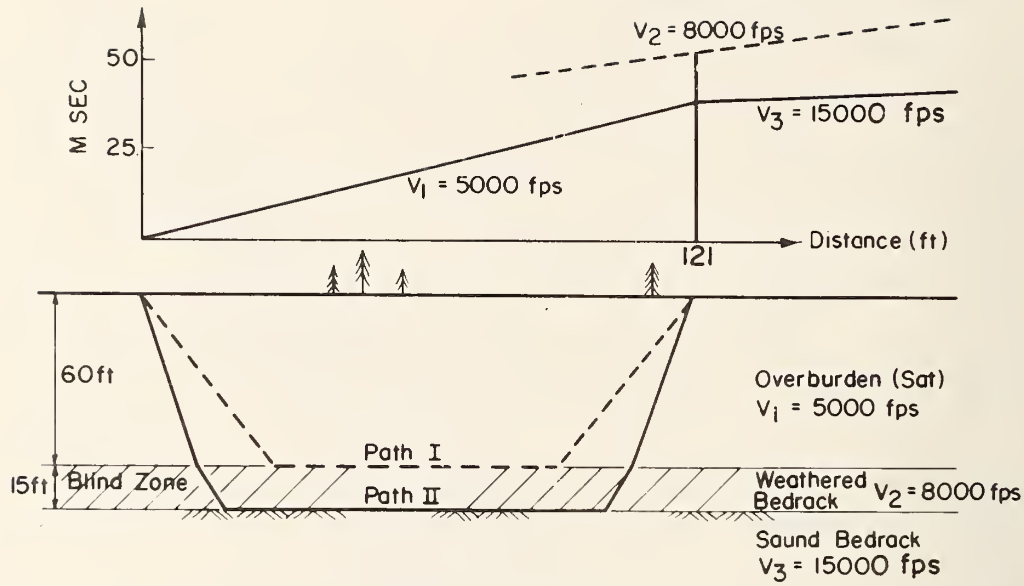
water characteristics. Geometry parameters are obtained mainly with geophysical exploration, whereas the soil and water parameters are obtained by contact testing.

Geophysical methods available for subsurface exploration today (1975) are all listed and discussed in Appendix J. Of all geophysical approaches, seismic methods were found to be most promising for geometry exploration in soft ground, and had proven, on-shelf components to fit the size and compatibility constraints of horizontal boreholes. Compared with seismic work in rock, the expected resolution in soft ground is limited. The main reason for this limitation is the higher attenuation (damping) of high frequency waves in soil.

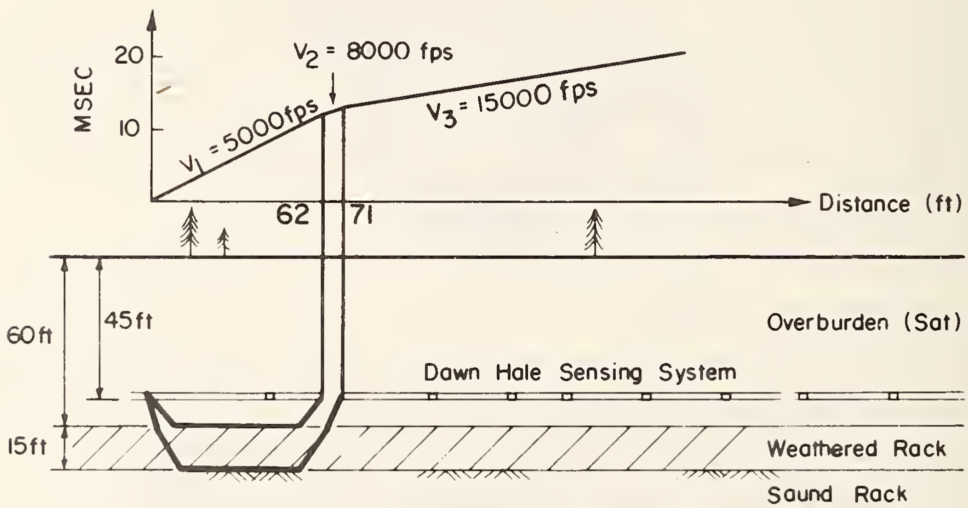
Seismic exploration from horizontal boreholes can be divided into two phases: (1) avoidance of obstructions (e.g., boulders) during excavation and (2) exploration for the design of the future tunnel. Avoidance of smaller objects does not appear feasible with evolutionary development of present equipment, whereas exploration can be performed during and after excavation and is feasible.

The advantages of exploration by seismic refraction in a horizontal hole below the surface are shown in Figure 1.4. Shallow irregularities of seismic velocity (i.e., changes in water table and occurrence of fill) are avoided and zones of intermediate velocities or "blind zones" (i.e., weathered rock) can be detected.

Monitoring the performance of the excavation equipment will yield index information concerning the soil-water parameters. Penetration rate, type of cutting, torque and normal force measured on the drill bit and load-deformation curves from the thruster's anchor pads can indicate soil "stiffness" and soil type. Due to the disturbance of the soil surrounding the borehole, the radial load-deformation relationships will not yield actual strength of the in situ soil. The contact testing device found most suitable and feasible to mount on the excavation equipment is the piezometer cone. Pore pressure variations and soil resistance could be measured during penetration. Permeability and static pore pressure can also be measured, but require stopping at least 5 minutes and up to 3 hours, depending on the soil permeability.



a) SURFACE REFRACTION SURVEY
(Never see "Blind Zone")



b) DOWN-HOLE REFRACTION SURVEY
("Blind Zone" - Visible)

1 ft = .304 m

FIGURE 1.4 BLIND ZONE DETECTION WITH DOWN-HOLE SENSING

If stability of horizontal boreholes can be ensured as discussed in Appendix H, exploration packages could be pulled through the borehole after removal of the excavation equipment. Sidewall sampling, geophysical (electromagnetic nuclear response) logging, seismic survey, resistivity survey, and caliper surveys are all feasible for follower packages. Retrieved sidewall samples will be disturbed, but are suitable for index tests, soil classification, and remolded strength tests. The electromagentic nuclear response may correlate with the soil permeability and with further development may prove to be a tool for direct measurement of soil permeability. Seismic exploration has already been mentioned. Two to four calipers can be placed at selected locations in the borehole, and the borehole deformations measured as a function of time with constant or decreasing mud pressure. Thus valuable information about the stand-up behavior of a subsequent tunnel can be obtained.

1.4 ALTERNATIVES AND ATTRIBUTES--SYSTEM ANALYSIS SUMMARY

Alternatives and attributes are best discussed with reference to Figure 1.5. The figure is divided into two halves. Resultant System Alternatives are presented on the left in a decision-tree format and the Attributes are presented on the right at the ends of the tree branches. After presenting a scenario for horizontal exploration, Figure 1.5 will be discussed in detail, column by column. This discussion introduces the considerations and summarizes the results. Because of differences in the variations of the attributes in Figure 1.5, use of this figure without further reading is not recommended.

SCENARIO FOR HORIZONTAL EXPLORATION

Since some 50 to 60 miles (80 to 96 km) of soft ground subway tunnels and 20 miles (32 km) of cut and cover and/or soft ground highway tunnels are projected to be built within the next ten years, the urban tunnel environment was chosen for the analysis of the value of exploring horizontally. Horizontal exploration is likely to be employed <u>after</u> the collection of historical subsurface information and preliminary geophys-

RESULTANT SYSTEM ALTERNATIVES / ATTRIBUTES *

EXPLORATION MODE	SEQUENCE OF EXPLORATION	PROPULSION TYPE	HOLE STABILIZER	DOWN-HOLE MOTOR	NAVIGATION		DEVELOP COST ($1000) Objects	DEVELOP COST ($1000) Running Ground	OPERATE COST ($/ft) 75 ft Depth	OPERATE COST ($/ft) 150 ft Depth	SUBJ. VALUE ($/ft) Objects	SUBJ. VALUE ($/ft) Running Ground
HORIZONTAL BORING	Complete Excavation only	Mandrel	Wash Pipe	Dyna Drill	Incremental	1	0		59	63	350	
		Mandrel	Wash Pipe	Dyna Drill	Continuous	2	250		53	57	"	
		Mandrel	Mud Only	Dyna Drill	"	3	350		"	"	"	
		Mandrel	Mud Only	Hydraulic	"	4	400		"	"	"	
		Thrust Applicator	Mud Only	Hydraulic	"	5	525		49	53	"	
	Complete Excavation With Separate Follower	Mandrel	Wash Pipe	Dyna Drill	Incremental		Same as Excavation only but add		68	73	500	800
		Mandrel	Wash Pipe	Dyna Drill	Continuous				62	67	"	"
		Mandrel	Mud Only	Dyna Drill	"				"	"	"	"
		Mandrel	Mud Only	Hydraulic	"				"	"	"	"
		Thrust Applicator	Mud Only	Hydraulic	"		150	180	54	63	"	"
	Simultaneous Excavation And Sensing	~~Mandrel~~	~~Mud Only~~	~~Hydraulic~~	~~"~~							
		Thrust Applicator	Mud Only	Hydraulic	"	6	775		62	67	500	~~800~~ 1100
Vertical Boring	300 ft (91m) Spacing								3	8		
	50 ft (15m) Spacing with Cone Penetration @ 10 ft (3 m) Spacing							35	71	152	350	800
Geophysical Exploration	Surface Refraction								1.5	1.5		
	Vertical Hole Refraction — 100 ft (30 m) Spacing								15	29	125	

* Variances of Attributes vary widely. Readers may wish to modify Subj. Value after reading.

1 ft = .304 m

FIGURE 1.5 COMPARISON OF EXPLORATION SYSTEMS

ical exploration, and during preliminary design. The primary data sought are: geohydrological (running ground), object location (rock and utilities) and strength-deformation characteristics. It is this environment which forms the backdrop for the following discussion.

RESULTANT ALTERNATIVE SYSTEMS

The horizontal exploration mode alternatives were economically compared with common vertical modes. The details of the operational costs are presented in Chapter 4 and Appendix M.

The sequence of exploration alternatives involved technical as well as economic comparisons. The technical considerations of size and operational compatibility, attenuation of seismic and acoustic waves, hole stability and hole disturbance are presented in Chapter 3 and Appendices H through K. Cost data is presented in Chapter 4. The technical considerations involved considerable detail and provide background for choosing equipment to be placed in the sensing module spaces (including the separate follower alternative). The module approach provides maximum sensing flexibility. Locations are listed on page 2-26.

The excavation equipment alternatives (Propulsion through Navigation) again involved both technical as well as economic comparisons. The technical considerations of size and operational compatibility, maneuverability, penetration, provision for module spaces, and geological compatibility are presented in Chapter 2. The excavation systems are of three diameters; System 1 the enclosed, no-development-cost alternative delivers a 3 in. (7.6 cm) diameter hole. Systems 2 through 5 deliver a 4.5 in. (11.4 cm) hole because of navigation system and fluid flow requirements. System 6 must involve at least a 7.5 in. (19.5 cm) to provide a sensing module space in the bit. The hydraulic motor is the only motor which will permit use of the bit module space.

Continuous navigation is possible with both the mandrel system (signals transmitted through the non-rotating mandrel or drill steel) and the thrust applicator system (signals transmitted through cable). However, the mandrel communication system is not compatible with

simultaneous exploration sensing and excavation. Simultaneous exploration sensing is not compatible with pulsed data transmission. Thus this branch of the tree is pruned or eliminated as shown by the hatched box.

The remaining 6 systems and 3 exploration sequences are all that remain of the 676 possible combinations at mid study. The 6 systems consist of essentially mandrel or normal force development with various combinations of equipment shown in Figure 1.2. Thus, there are only two systems with alternate modes of use and interchangeable equipment.

Maximum penetration distance is a function of bit wear which is a function of geology. The thrust applicator system may be limited to 800 ft (244 m) in gravelly or bouldery soils, but could reach 2000 to 3000 ft (610 to 915 m) in clays and sands with further development. The mandrel system allows change of bits within the washover pipe and could penetrate to 2000 to 3000 ft (610 to 915 m) even through boulders provided the washover pipe is fitted with a bit. Of course, the washover pipe must be withdrawn before follower sensing is possible.

ATTRIBUTES

Development costs are lower bound estimates but are sufficient to internally compare the alternatives because of the commonality of needed component development. Components of the development costs are listed in Table 1.1 by the system number shown in Figure 1.5. Details are given in Chapter 5.

The follower package approach allows for adaptability for object identification. Thus, follower development costs must also be considered. Once a stable hole (?) is established, various followers (i.e., resistivity packages) can be pulled to differentiate metalic from non-metalic objects. In addition, followers could be employed in combination with simultaneuous sensing and excavation for even greater reliability. With this dual approach, the "value" of system 6 for running ground could be increased from 800 to 1100 \$/ft (2600 to 3600 \$/m). Present costs of exploring with follower packages are discussed in Section 4.4.

TABLE 1.1

ESTIMATE COMPONENTS OF DEVELOPMENT COSTS

SYSTEM	COMPONENT	COST
2	Communication Only	150,000
	Gyro Navigation System	100,000
3	Same as System 2	250,000
	Field Test for Mud	100,000
4	Same as System 3	350,000
	Hydraulic Motor	50,000
5	Field Test for Mud, etc.	100,000
	Gyro Navigation System	100,000
	Thrust Applicator Mod.	100,000
	Articulated Flexer	75,000
	Hydraulic Motor	50,000
	Adaptable Bit	100,000
6	Same as System 5	525,000
	Cone Piezometer	100,000
	Seismic System	100,000
	Dump Value	50,000
Follower:	Field Test	100,000
Objects	Seismic System	50,000
Follower:	Field Test	100,000
Running	Inductance	30,000
Ground	Caliper	50,000

Operating costs are summarized in Chapter 4. The detailed assumptions are contained in Appendix O. The basic costs in Appendix O were increased to reflect extra excavation to get to grade (see Chapter 2 for maneuverability) so that costs could be presented in dollars per foot explored of a 2000 ft (610 m) tunnel. In addition, System 6's operating costs were increased by $7/ft (23 $/m) to account for simultaneous sensing crew and data reduction costs, and $3/ft (10 $/m) to account for decreased penetration rates. Development costs were not included in the operating costs except for the existing mandrel system which must recover past investment on any future excavation. Operating costs will increase at shallow depths where hydraulic fracture occurs. See Appendix N for details.

Operating costs for the comparative vertical methods of exploration can be found in Section 4.3. The costs of vertical hole refraction is high because the costs of drilling holes in addition to those spaced at 300 ft (92 m) is included. The range in possible operating costs is indicated by the very inexpensive nature of surface refraction. Unfortunately, the value of such exploration for the particular cases of obstacles and running ground is comparatively difficult to estimate.

Subjective Values of the information obtained with the exploration system were obtained from case studies of cost overruns resulting from unanticipated subsurface conditions. These cost overrun data are valuable to design engineers and are summarized in Chapter 4. The assessment of the <u>sufficiency</u> of exploration equipment and interpretation to detect the unfavorable conditions cannot be objectively assessed. Thus, the case study results were subjectively modified to reflect differences in the exploration approaches. The maximum Values are for 20 ft (6 m) diameter tunnels. However, the details of the methodology and case studies are presented in Appendix L so that the data can be applied to different diameter tunnels.

Object detection could save up to 500 \$/ft (1640 \$/m) (savings is the Value). Only the systems involving horizontal seismic exploration were judged capable of saving the maximum amount. For instance, excavation/penetration only might require two passes, one at the invert and one at the top of the tunnel, depending upon stratification and relative elevations of the soil-rock interface and the track. Running ground detection could save as much as 1100 \$/ft (3060 \$/m). Only simultaneous excavation and exploration with a piezometer cone and subsequent caliper follower were judged capable of saving the maximum amount. Note System 6's operating costs should be increased by 7 \$/ft (23 \$/m) to account for subsequent follower study which enables the Subjective Value to increase from 800 to 1100 \$/ft (2600 to 3600 \$/m).

The Attributes of any system can be internally compared by dividing the Value by the Operating Costs. Development costs can be added to the Operating Costs by judging the "firmness" of the exploration market outlined in Table 4.1 and dividing the development costs by the footage

of the expected market. Details of this methodology are presented in Appendix P. Because of differences in the variations of the Attributes, differences between Value/Cost ratios should be 3 to 4 to be significant.

1.5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE ACTION

This section is prefaced by recommendations for future action regarding the overall developmental approach for soft ground. Then conclusions and recommendations will be briefly summarized by major headings: Excavation, Exploration, and Economics. These conclusions and recommendations are detailed in Chapter 5.

RECOMMENDATIONS FOR OVERALL EXPLORATION APPROACH

The most cost effective action resulting from this study would be extensive notification of design engineers of the extremes of the possible cost overruns, and the importance and cost effectiveness of adequate pre-excavation exploration. This step is necessary regardless of the method of exploration, be it vertical or horizontal. Refer to Chapter 4 for details of comparative cost overruns.

Shallow tunnels (75 to 100 ft / 25 to 30 m) are best explored vertically--except in environmentally sensitive areas or where access is limited. Therefore, development of vertical and horizontal exploration methods should be weighted by the percentage of expected shallow and deep (or environmentally sensitive soft ground tunnels) tunnels.

Development of a combination penetration and exploration system is not recommended. The interface and component development costs would be high without increases in the value of subsurface information gained above the level obtained by complete excavation and separate followers. Investment in the excavation system for horizontal boring should take precedent over that in the exploration systems. Without an inexpensive hole, advanced exploration equipment is not cost effective.

The mandrel system--with zero development cost--can place a 5 in. (12.5 cm) pipe out to 1700 ft (520 m) in non-bouldery environments and

could place similar diameter holes out to 2000 to 3000 ft (610 to 915m). It should be employed in a simple field test to

1) verify hole stability
2) provide a hole to test thrust applicator
3) check exploration approaches, and
4) check cost projections

If stable holes can be field proven, then horizontal boring/penetration with follower packages is the most cost effective approach to explore deep soft-ground tunnels.

EXCAVATION

<u>Conclusions</u>: The mandrel system with its washover pipe is the most adaptable system. It is operable today out to 1700 to 2000 ft (520 to 610 m) in soil. The washover pipe is the principal feature limiting longer penetration along paths involving sharp curves. The thruster system has potential to penetrate further along a tortuous path but is less adaptable. It is presently not operable in soil but has penetrated 800 ft in soft coal. The mandrel system involves the largest initial cost and the least developmental costs whereas the thruster has the least initial cost and the largest developmental cost. Operational costs for the two systems are similar.

Neither system is readily combinable with on-board sensing because of the requirement of stopping for most testing and sensing. If excavation is stopped without provision for continuous fluid movement, the suspended hole cuttings will begin to settle. Advance after stopping requires 1) abnormally high fluid pressure which leads to hydraulic fracture and 2) higher normal forces due to jamming of the cable or drill steel with the settled fines.

<u>Recommendations</u>: The final development of an economic, cableless bit communication system would enable cost reduction of mandrel drilling by at least 10 to 15%. This development cost should be shared with the U.S. Bureau of Mines. The thruster system avoids communication difficulties because of its continuous cable connection.

There are three other excavation subsystems whose further development would increase the efficiency of horizontal drilling in soft ground. The first two pertain to both the thruster and mandrel systems. Penetration distances in residual soil or bouldery till will be limited by bit wear. Therefore, a combination soil-rock bit with side cutting capability should be developed. The reduction of the size of the Dyna-Flex articulated bent sub and incorporation of the bent housing concept would significantly improve directional control. Finally, development of a variable contact pressure system for the anchor pads of the thruster is necessary for thruster penetrations in variable soils.

EXPLORATION: HOLE STABILITY

Conclusions: Continuous excavation with subsequent geophysical and contact sensing will involve both lower operating and development costs than on-board sensing. The costs will be lower because of decreased technical difficulties and less interference and interaction of excavation and exploration personnel. The most valuable follower packages for sensing were described in Section 1.3.

Hydraulic fracturing limits the technical feasibility of horizontal boring at shallow depths. Over-consolidated clays are the least susceptible while normally consolidated clay's susceptibility is a function of the excavation system. Sand is especially susceptible as evidenced by the difficulties encountered by Titan Contractors during the crossing of the Cerritos Channel. See Appendix N.

The cone piezometer and nuclear response logging could be adapted to continuous excavation. All other exploration approaches either require stopping between 2 and 120 minutes (see Table 4.3) or yield parameters which are inexact due to hole disturbance or inherent measurement limitations.

As shown in Figure 1.4, geophysical exploration from horizontal holes enables detection of weathered rock (blind zones) and increases accuracy. Attentuation characteristics of geophysical equipment preclude detection of obstacles far enough in advance to eliminate backing up.

Recommendations: The feasibility of pulling a follower package through a pre-excavated hole should be investigated through a field trial. If packages can be pulled, then development of follower packages should be pursued. The most valuable follower packages are the seismic refraction/reflection and caliper packages. See Chapter 3 for details of recommended systems.

The cone piezometer should be developed. The piezometer and anchor pad deflection are the only contact sensing devices able to operate without stopping. In addition, the cone is adaptable to vertical exploration methods.

ECONOMICS

Conclusions: The costs of ineffective exploration are high. Figure 4.3 gives the marginal costs of three typical unanticipated subsurface conditions: running ground, boulders, and utilities. Of these 3 cases, costs of running ground are the greatest. Therefore, pre-excavation knowledge of running ground is the most valuable.

These costs per foot are high FOR THE LENGTHS OF TUNNEL WITH THE MALADY. The principal difficulty in exploration is predicting the distribution of these zones of adversity. If these zones are at all likely after initial exploration, exploration costs indicate that horizontal boring or any additional exploration to pinpoint the area is beneficial. The greatest difficulty stems from determining where additional exploration effort should be expended.

Costs of conventional exploration methodologies given in Chapter 4 indicates that tunnels shallower than 75 ft to 100 ft (23 to 30 m) are best explored with vertical techniques. However, horizontal boring is cost effective for deeper tunnels or in environmentally sensitive areas (i.e., parks and densely constructed neighborhoods) where vertical access is difficult.

Recommendations: The most difficult aspect of any value analysis of an exploration method is determination of the probability of particular adverse conditions at sections along the tunnel. It can be demonstrated that when the probability is 1, any extended exploration program is cost effective. Calculation of cost effectiveness when this probabil-

ity is unknown is speculative. More effort should be placed in comparatively obtaining these probabilities of the states of nature from case study data for differing geologies and exploration methods.

1.6 SCOPE OF INVESTIGATION

PARTICIPANTS

Developing maneuverable horizontal penetrators, MPS's, (Excavation) involves transferring technology from the petroleum industry (well drilling) and the aerospace industry (navigation and guidance) to civil construction. To initiate that transfer, M.I.T. combined efforts with Titan Contractors, experienced directional drillers of oil wells and the nation's only commercial driller of directionally controlled horizontal holes; and the Draper Laboratory, designers of the navigation systems for the Apollo and Trident spacecraft.

Coupling exploration with penetration (Exploration) involved the application of contact and geophysical sensing principles to horizontal holes. Contact sensing, attenuation, and hole stability are M.I.T.'s area of specialty, and Weston Geophysical Engineers, Inc. acted as consultant for the field application of geophysics.

The systematic evaluation of project alternatives (Economics) has been a primary area of interest in the Department of Civil Engineering at M.I.T. for the past 10 years. The expected costs of the penetration systems have been projected through construction observations and visits: Titan's Cerritos Channel crossing and CONOCO's maneuverable coal mining device.

This investigation has combined the strengths of academia (theoretical analysis, research through creation, and disinterested-party assessment) with the strengths of practice (detailed knowledge of existing and possible machinery and day-to-day project management). Thus, the results reflect what is, as well as what can be. The resources expended summarized the state-of-the-art in a growing field and projected its future.

COMPONENTS

Many of the subsystems required for economical horizontal penetration and exploration already exist, but lie unconnected in separate disciplines. Some of these subsystems, being developed by private capital, require huge investments. For instance, TELECO is developing a mud pulse data transmission system to eliminate wire lines and has invested some 2 to 3 million dollars in this subsystem alone. Therefore, to ensure total system economy, the scope of this investigation has been restricted to existing, prototype-sized hardware and developed, applied-successfully-at-least-once technology. Also, because of NSF funding of novel excavation devices, the investigation was restricted to mechanical excavation systems.

PRELIMINARY DESIGN

The preliminary designs offered ensure geometrical and operational compatibility. No intent has been made to duplicate manufacturer's drawings. The equipment examples cited by name are compatible but their citation does not preclude use of equipment of similar size and operating characteristics. Citation of suppliers and trade names does not imply endorsement by the Department of Transportation or by the Massachusetts Institute of Technology.

SOFT GROUND/SOIL

This investigation was limited to penetration/excavation in soft ground. Soft ground for this study was defined by four environments. The first was loose sand and/or soft clay transported soil. The second was dense sand and/or stiff clay transported soil. The third was residual soil or glacial till containing cobbles and boulders. The fourth is not directly related to geology but rather to the presence of man-made objects in the three above conditions. This fourth environment is very similar to the third.

1.7 GUIDANCE TO READER

The report is divided into three general sections: (1) An introduction/executive summary--Chapter 1; (2) A 100-page presentation of the entire project--Chapters 2, 3, 4, and 5; and (3) Appendices containing details, assumptions, and example calculations. Chapter 2 summarizes the aspects of the study devoted to excavation equipment which are detailed in Appendices D, E, F, and G. Chapter 3 summarizes the aspects of the study involving exploration and related borehole disturbance which are detailed in Appendices H, I, J, and K. Chapter 4 summarizes the economic aspects of the study as detailed in Appendices L, M, N, O, and P. Chapter 5 contains the conclusions and options for further action.

Appendix A contains references and Appendix B contains the names of contributors of information to this study. Appendix C contains a limited glossary of terms peculiar to the specialized disciplines involved in this study.

Readers interested in a particular appendix who do not have a background in directional drilling and/or exploration should first read the chapter in which the appendix is summarized.

CHAPTER 2

PRELIMINARY FEASIBILITY DESIGN MANEUVERABLE PENETRATION SYSTEM

2.1 INTRODUCTION

CONTENTS

This chapter presents developed (or prototype tested) borehole navigation and excavation equipment. The combination of this equipment makes maneuverable horizontal penetration/boring technically feasible. The process of optimization and numerical bases for selection of four systems is also presented. The chapter closes with design compatibility drawings for the two most feasible systems.

Feasible drilling equipment is presented in Section 2.2

Feasible navigation and communication equipment is summarized in Section 2.3. Current borehole navigation and communication equipment is surveyed, and a preliminary design is presented for a gyroscopic navigation unit which meets the requirements of horizontal drilling. Three advanced bit communication systems for rotary drilling are reported, and a simple navigation approach for near-surface work is presented.

Uphole configuration of equipment is briefly discussed in Section 2.4. The surface space requirement was not treated in depth because of larger flexibility of uphole space compared to that downhole.

The selection process for determining the most technically feasible excavating system is presented in Section 2.5. Since uphole space is not as critical as that in-hole, it was not considered as a constraint. The four most feasible designs were chosen on a basis of optimizing drillability in a particular geology. These systems were then numerically evaluated for their excavating, hydraulic fracturing, and maneuverability efficiencies.

GUIDANCE TO READER

The detailed information supporting the summaries and conclusions in this chapter can be found in Appendices D, E, F, and G. The appendices taken as a whole treat excavation/penetration equipment and methods. Readers without a background in directional drilling should read this summary chapter before turning to the appendices.

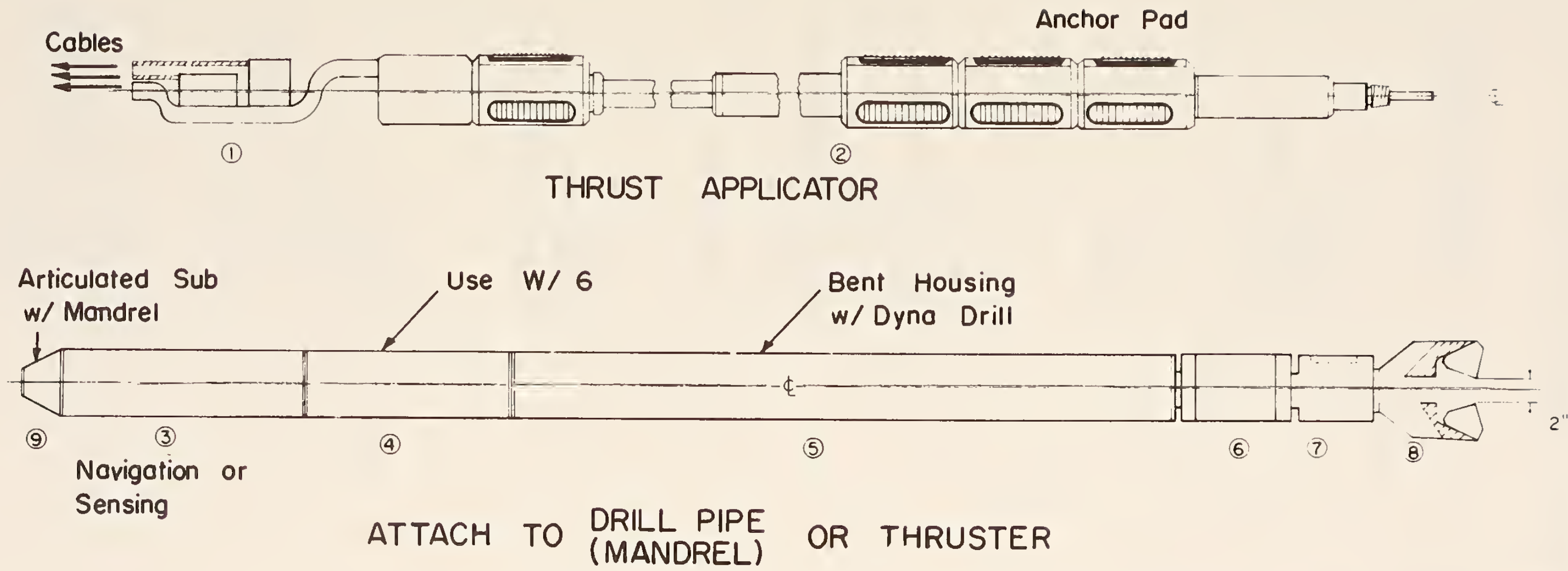
2.2 FEASIBLE DOWNHOLE EXCAVATION EQUIPMENT

This section briefly presents motors, thrusters, direction changers, bits, and cables considered feasible for maneuverable penetration. The relative positioning and shape of this equipment is shown in Figure 2.1. The components and possible sources are listed in Table 2.1. A more detailed description of downhole equipment can be found in Appendix D. Due to the large number of available drill bits, specific manufacturers should be contacted. In addition, since there is only one deflection shoe device, one articulating sub, and one fixed angle bent housing available on the market, detailed drawings of the directional control equipment can be obtained from the respective manufacturers found in List of Contributors, Appendix B.

DOWNHOLE MOTORS

Three out of the four downhole motors presented in Appendix D are considered feasible for drilling a horizontal hole in soft ground. They are the Dyna-Drill, the W. H. Nichols hydraulic pump motor, and the Century electric motor, shown in Table 2.2. These specific company names do not imply that there exist no other suitable alternatives. However, other alternatives should have similar design features.

The Dyna-Drill is a well-accepted and proven mud hydraulic motor used in directional drilling for oil wells and river crossings. The W. H. Nichols hydraulic motor and the Century Electric motor have both been preliminarily tested for drilling soft coal; therefore, they should both be readily adaptable for drilling in soft ground. The turbo-drill was not considered a feasible soft ground directional drilling motor because of its excessive weight, lack of an indication that it has



The mandrel is a non-rotating drill pipe of smaller diameter than the hole. It transfers thrust from the uphole drilling platform to the illustrated down-hole components, and is protected by the washover pipe. See page N-10 for the geometrical details of mandrel and washover pipe and N-2 and N-19 for the platform.

	COMPONENTS
1	Downhole hyd volving
2	Thrust applicator
3	Electronic package
4	Orientoting motor
5	Hyd drill motor
6	Deflection Shoe
7	Bit sub
8	Tricone core bit
9	Bent sub

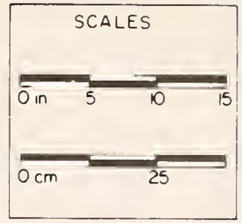


FIGURE 2.1 PROPOSED DOWN HOLE EQUIPMENT

TABLE 2.1

COMPONENTS FOR MANEUVERABLE PENETRATION SYSTEMS

COMPONENT	POSSIBLE SOURCE
DOWNHOLE MOTORS	
POSITIVE DISPLACEMENT PUMP	Dyna-Drill
HYDRAULIC PUMP	Nichols
ELECTRIC	Century - REDA
TURBINE	Numerous
NORMAL FORCE DEVELOPMENT	
UP-HOLE DRILL CARRIAGE	Titan
IN-HOLE THRUSTER	DRILCO
DIRECTION CHANGERS	
FIXED	
Bent Sub	Numerous
Bent Housing	Dyna-Drill
Whipstock	Numerous
CHANGEABLE	
Articulated Bent Sub	Dyna-Flex
Deflection Shoe	CONOCO, DRILCO
JET BITS	Numerous
BITS	Numerous
HOLE STABILIZATION	
NONE (COAL-SHALE)	CONOCO
WASHOVER PIPE (SOIL)	Titan
SLURRY (SOIL)	Future Emphasis
COMMUNICATION	
DRILL STRING PULSE (400 Hz)	Telcom
GROUND PULSE (25 Hz)	Raytheon
MUD PULSE	Raymond Prec.
CABLE	
Straight	Sperry Sun - CONOCO
Reel	Exxon (?)
NAVIGATION (POSITION SENSING)	
PENDULUM	Numerous
MAGNETIC COMPASS: PENDULUM	Sperry Sun, Eastman, Kuster
MAGNETOMETER: PENDULUM	Sci. Drill: Telcom
GYRO: PENDULUM	Numerous
SURFACE SEISMIC	Weston Geophysical Engrs.

stalled on the bottom of the hole, and the probable binding of the rotor and stator under a bending load induced by a sharp turn in the drill path.

The Dyna-Drill can endure some bending induced by sharp turns in the drill path (because of its rubber stator), but not for extended operation. With time and excessive curvature, the effects of bending a Dyna-Drill will lead to the deterioration of the stator. The vibration of the motor can interfere with the geophysical and navigation equipment that would be attached to the maneuverable penetration system.

Another factor limiting Dyna-Drill's application to a system which explores while drilling is the extreme difficulty in connecting an electric cable to the uphole, free end of the rotor. The seemingly insurmountable difficulty of threading a static, non-rotating wire through an eccentrically rotating shaft precludes inexpensive use of the bit module space (shown in Figure 2.1) with the Dyna-Drill. This module space can house geotechnical or geophysical sensing equipment as explained in Appendices J and K. A later section will deal with available module spaces in the various proposed MPS's.

The W. H. Nichols hydraulic motor could be the most adaptable of the three downhole motors recommended for soft ground horizontal drilling. It is a relatively short motor (i.e., 4 ft/1.2 m in length) and yet it still develops a very high torque output for a low flow rate. Shortness and low flow rates are optimal features for downhole motors. In addition, this motor has a concentrically rotating shaft which allows electric sensing wires to pass through the motor to the previously mentioned bit module space. The concentric shaft and smooth operation of the gerotors reduce the external vibration.

Finally, the electric motor allows a reduction in the trailing cable weight of the DRILCO thrust applicator by reducing the size of the slurry hose while still providing the same drillability characteristics of the two previously mentioned motors. However, the electric motor requires a reduction gear box between the motor and bit to reduce the bit RPM. A wire cannot be passed through the reduction gear box; therefore, the forward bit module is inaccessible. Another minor

problem with the electric motor is its susceptibility to overloading and shorting before corrective action could be taken by the drillers.

Even with the above-mentioned drawbacks of each motor, all of the recommended motors will perform in a soft ground environment and can be used for directionally controlled horizontal drilling.

TABLE 2.2: SMALL DIAMETER DOWNHOLE MOTORS FOR SOFT GROUND (SUBSTITUTIONS EXIST)

NAME; COMPANY	MECHANIZATION	DIAM. O.D. In. (Cm)	LENGTH Ft (m)	TORQUE Ft/lbs (m/N)	RPM	FLUID FLOW (GPM) (m^3/min)	WEIGHT lbs (kg)	COMMENT
DYNA DRILL DYNA DRILL	Reverse Moyno® Pump	2-3/8* (6.0)	8-1/3 (2.5)	30 (40)	1000	25 (.095)	75 (34)	Best for Soft Ground Penetration
		6-1/2 (16.5)	19.6 (6.0)	467 (633)	305	250 (.95)	1422 (646)	Large Hole Directional Drilling-for Comparison
SUBMERSIBLE PUMP CENTURY	Electric	3-3/4 (9.5)	4.7 (1.4)	175 (238)	3450 gear 150	(5 kw)	+ 50 100 (68)	Length includes 2' for Gear Box Can Stall with Little Feedback
GEROTOR	Internal Gear Positive Displacement Pump	5 (12.7)	4 (1.2)	175 (238)	300	30 (.11)	25 (11)	

R = Registered Trade Mark

THRUSTERS--NORMAL FORCE DEVELOPMENT

Titan Contractors' uphole thruster, Big Alice, is described in detail in Appendix N. Their drill carriage occupies the space of a semi-trailer but could be redesigned to be smaller. The uphole layout of a typical site is presented in Section 2.4.

The only full-sized, operationally-tested, downhole thruster presently available is the DRILCO thrust applicator. This thrust applicator has successfully drilled horizontal holes in soft coal with a compressive strength of about 1 tsf (95.7 kN/m^2). Two other thrusters, the WORM and

NURAT, have potential for application to soft ground drilling, however, they are still in the early development stages.

In order for the thrust applicator to operate in soft ground, it must be designed specifically for that purpose. The 5 3/4 in. (14.6 cm) O. D. model, in its present configuration, can operate in very stiff clay or compacted, cemented sands but not in soft clay or loose sands. As mentioned in Appendix G, a possible redesign of the thruster pads could improve the operation of the 5 3/4 in. (14.6 cm) O. D. thruster in clays.

The DRILCO thrust applicator cannot undergo bending stresses for any extended period. Two problems are created in bending: (1) the piston rod will bind and will be difficult to reset, and (2) in stiff materials, the outer body may be wedged in the bend.

The drilling system, WORM, has considerable potential, if developed and satisfactorily tested. The basic concepts and principles of operation appear to make the system a feasible one for future application to horizontal drilling. Although least is known about the NURAT thruster, it too has the intuitive potential of being successfully applied to horizontal drilling. The major problem to be resolved with NURAT is direction control. However, neither system has been field tested and will therefore involve additional development exnenditure.

Of the above mentioned equipment, the downhole thruster to be adopted for the final equipment design will be the DRILCO thrust applicator.

DIRECTION CHANGERS

Three of the direction control devices that were presented in Appendix D are considered feasible for horizontal drilling in soft ground. They are the bent housing, the articulated bent sub, and the CONOCO deflection shoe.

The important question is, in what situation can these individual control devices be successfully applied? The bent housing with the fixed angle is most efficiently adapted to the slim mandrel system because of

the flexibility of the motor and bit. The bent sub's side force is taken up in flexing the motor. See Appendix G for an explanation of the operating principles of the bent sub and housing. On the other hand, the deflection shoe is ideally suited for the thrust applicator system because of its self-contained ability to apply a lateral force to the bit.

The articulated sub is limited by its present minimum diameter, 5 in. (12.7 cm) and minimum length, 8 ft (2.4 m). Another limiting factor is the requirement of a special locking probe which will interfere with any survey system, except the single shot magnetic method of navigation.

An articulated sub or housing will require significant redesign to be compatible with the rest of the system. However, for penetration in very soft soils, it would be more advantageous than the deflection shoe--especially if it can be electrically actuated and placed in front of the motor.

DRILL BITS

The three basic types of drill bits available today and applicable to soft ground penetration are the tricone roller, diamond, and drag bits. Each of these bits is feasible for horizontal drilling in soft ground and like the direction control devices, each one has a specific application. A fourth bit, the compax bit--a toothed diamond bit--is under development and may be useful in residual or mixed soils.

The tricone roller bit provides maximum cutting ability with its deep cut, chisel-shaped teeth, while the roller bearings within each of the cones (as shown in Figure D.16) reduces the torque requirements for cutting. The reduction in torque requirements allows for the most efficient transfer of motor output torque into shearing force at the outer edged heel teeth. These heel teeth are responsible for lateral excavation and thereby make the tricone the most efficient directional drilling bit. However, a major requirement for successful drilling is freeing the deep cut teeth from clogging in clay or silty soil. Therefore, the drill fluid nozzle design on the tricone bit becomes a critical item for maintaining clean roller cone teeth. High stream velocities

cannot be used because of their tendency to erode the bit face in soft ground. A further consideration when using a tricone bit is the maximum operational RPM. A general rule of thumb places an upper limit of approximately 500 RPM.

A major advantage of the cone roller bit design is the space that exists in the center of the bit, as shown in Figure 2.2. The bit shown here is a quadricone but is also available in a tricone version and is presently used as a coring bit. Smith Tool Company currently produces a 10 1/8 in. (25.7 cm) O.D. with a 2 1/2 in. (6.4 cm) core. However, with retooling, the smallest core bit they could produce would be a 7 in. (17.8 cm) O.D. with a 2 in. (5 cm) core (Gardner, 1975). The advantage gained by adopting this core bit design is the availability of the module space where the soil sample would normally be collected. Detailed explanation of the various geotechnical and geophysical instruments adaptable to this module space is found in Appendices J and K.

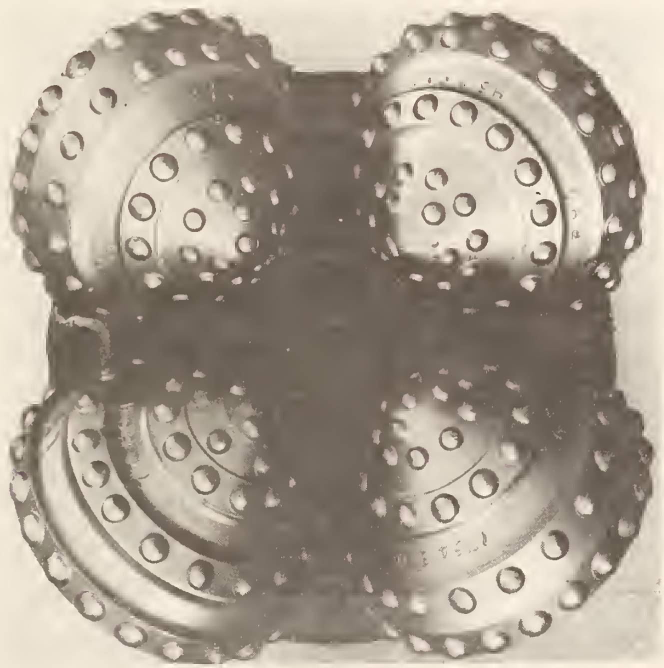


FIGURE 2.2 CORING BIT
(COURTESY SMITH INT.)

The drag bit is an acceptable bit for drilling in soft ground. Because of the long outer edge of the cutting face (shown in Figure D.16), the drag bit requires more torque than a tricone to drill in the same formation. For this reason, the drag bit becomes inefficient in larger diameter holes. The boundary size is a function of the bit-motor combination and the type of formation being drilled. The shearing parameter, presented in Section 2.4 will provide a means of analyzing this effect.

Finally, the diamond bit is successfully applied in drilling soft ground when the bit RPM is in excess of 500 RPM and core stones and boulders are expected along the drill path. The diamond bit allows continuous drilling through residual soils for a longer distance than either a tricone or drag bit because it can penetrate core stones, whereas the drag bit cannot, and the tricone will wear rapidly unless fitted with tungsten carbide button inserts. Excessive bit wear will require the MPS to be pulled out of the hole to change bits, thereby increasing drilling time and the possibility of hole collapse.

HOLE STABILIZING DEVICES

Presently holes are stabilized with a wash-over pipe and with drilling mud slurry. Titan employs the wash pipe and slurry. Washing over is similar to casing a hole with the drill rod (in this case the pilot bore) in place. This technique is described in Appendix N. Mud slurry stabilization is not employed to its fullest potential because of the risk of hydraulic fracture. Slurry stabilization is described in detail in Chapter 3 and Appendices F and H.

Other methods of stabilization were first considered: helical, plastic liners and soil melting (subterrene). Any downhole device except soil melting and slurry stabilization, adds another downhole device. In addition, any liner will interfere with the exploration phase. Since the objective of the system is economical exploration, systems which increased complexity (and cost) or interfered with exploration were not pursued further. Therefore, only the removable washover and slurry stabilization approaches were investigated extensively.

CABLES

When downhole thrust applicators provide bit normal force, the design of cables and hoses becomes primary to the success of the concept. The cables will transmit power and signals as well as provide a possible escape mechanism. The force required to pull a cable through a horizontal hole can be very high as shown in Appendix G and is nearly impossible to predict with any reasonable accuracy. Proper cable design is predicated on the solution of many related problems, including navigation system power and output signal requirements, hydraulic orienting system design, slurry composition, etc. The cable designer would like to minimize the number of conductors to limit the size of the final configuration. This would require additional downhole electronics for the navigation and sensing systems which, while feasible may overshadow cost advantages of a simpler cable and may introduce reliability problems.

Because of the types and number of conductors required, identifying a single, off-the-shelf cable to cover the range is impossible; it is even unlikely that a series of existing cables and hoses could be combined to yield a workable composite. Despite the cost and lead time required for manufacture, a special cable might be the best choice for this task. The advantages of developing a cable with almost neutral buoyancy and a self-righting force (eccentric center of gravity) are considerable. Pulling it through the hole would not tax the already limited thrusting capability of the DRILCO thrust applicator.

Table 2.3 lists possible conductor requirements. The navigation system draws, at most, a few tens of watts; the pressure sensors draw a few watts. Choices are indicated by normal and minimum figures and by OR, when a choice of one type of instrumentation over another is forced by physical compatibility. If the sparker cable is included, it may cause interference in other cable components. See Appendix J for a description of the geophysical system requirements.

Figure 2.3 shows the expected maximum cross-section of the cable. The cable should be neutrally buoyant and eccentrically balanced. The eccentricity will provide constant orientation for seismic pickups. In addition, the cable should contain a stress core to provide emergency retraction capability and prevent internal cable failure.

TABLE 2.3 CABLE REQUIREMENTS

System	Normal Channels/diameter	Minimum Channels/diameter
NAVIGATION		
3 Accelerometers	3 input, 6 output	2 input - output
1 Gyro	2 input, 3 output	
GEOPHYSICAL SENSORS		
5 Pressure Transducers	2 input, 10 output (one is common, in-out)	Same 2 as NAVIGATION
Cone Piezometer	Share cable w/pore pair	
Air Gun	¼" Dia 2000 PSI, hydraulic line →	same as normal
OR		
Sparker	1 high power cable (#00 wire) →	same as normal
	1 firing cable →	same as normal
DOWNHOLE MOTOR		
Slurry Hose	1, 1" (2.5 cm) diam →	
Hydraulic Control	2, ½" (1.2 cm) diam	1, ½" (1.2 cm) diam (future design)
	CHANNELS	CHANNEL
	25 input - output	2 input - output
	HOSES	HOSES
	1, 1" (2.5 cm) 2, ½" (1.2 cm) and 1, ¼" (0.6 cm) or 1, #00 cable and 1, firing cable	1, 1" (2.5 cm) 1, ½" (1.2 cm) and 1, ¼" (0.6 cm) or 1, #00 cable and 1, firing cable

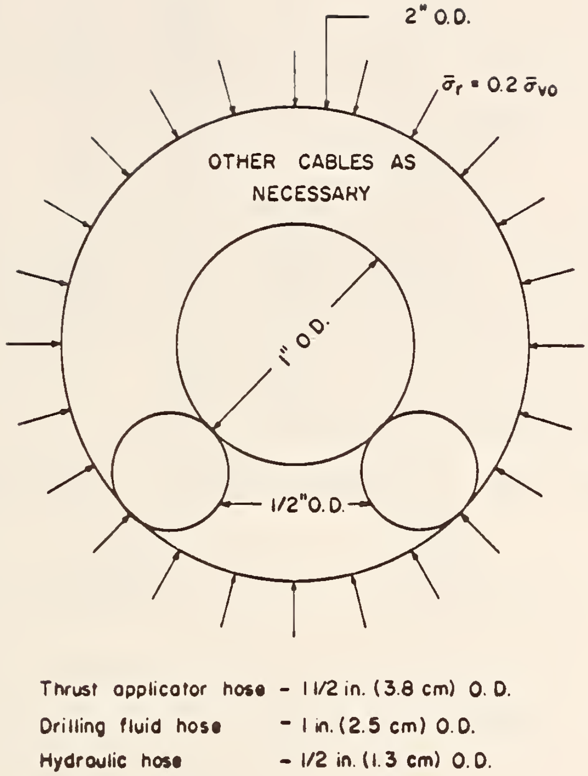


FIGURE 2.3 CABLE GEOMETRY

2.3 FEASIBLE NAVIGATION AND COMMUNICATION EQUIPMENT

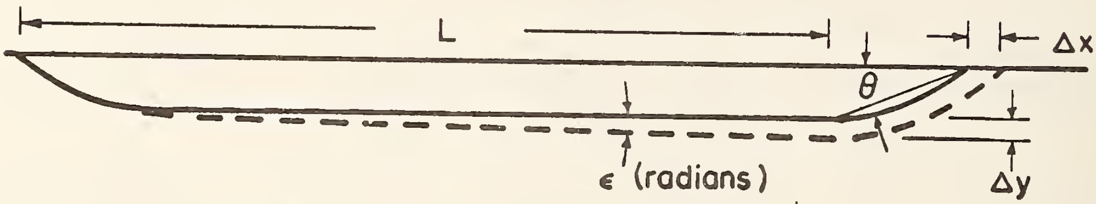
This section briefly presents navigation (position sensing) and bit communication systems which might be potential components of the penetration system. In addition, a preliminary design for a gyroscopic navigation system is presented which meets the requirements for horizontal penetration. A more detailed discussion of these systems is presented in Appendix E.

NAVIGATION/SURVEY EQUIPMENT

Currently available navigation equipment is assessed in Table 2.4. The most important factor, beside cost, is accuracy. Component accuracy is highly definable and associated systematic errors can be eliminated through calibration. Random (or field and operator) error cannot be

eliminated. For this reason exit point error can be 10 to 20 ft (3 to 6 m) in 700 (210 m) in urban environments (Titan experience), whereas systematic pendulum (accelerometer) error suggests it should be only 4 ft (1.2 m).

The model for this analysis is shown in Figure 2.4.



$\Delta Y = L\,\varepsilon \therefore \Delta X = \Delta Y \cot\theta = L\varepsilon \cot\theta$

FIGURE 2.4 POSITION ERROR ANALYSIS

The equipment accuracy, ε (radians), is given in Table 2.4. The entrance and exit angles, θ, employed by Titan are approximately 20°.

Three targeting accuracies are proposed to provide a range of possible system configurations and several bases for economic impact evaluation. As a rapid transit tunnel normally is on the order of twenty feet in diameter, the navigation system should be capable of identifying the position of the drill bit to within ten feet over the short course of 1000 ft. A more desirable goal, and one which is the general aim of the components specified in their appropriate sections, is ten feet in 5000 feet. The most demanding tolerance anticipated would not call for less than one foot in 5000 feet. In each of these specifications, equal emphasis is placed on azimuth and elevation uncertainties.

There are four main factors which affect choices of available systems: (1) Magnetic interference precludes magnetometers and magnetic compasses in urban environments; (2) Gyros precess; consequently, their error increases with time and must be updated or employed only on a single shot basis; (3) To eliminate systematic torquing of gyros, they must be gimbaled or suspended to eliminate influence of drill bit motion; (4) When a tool's inclination changes by 90°, more gyros and pendulum accelerometers may be needed, which increases the unit's size.

TABLE 2.4 AVAILABLE NAVIGATION EQUIPMENT

NAME AND COMPANY	MECHANIZATION	DIMENSIONS	POWER REQ'TS	ANGLE LIMITS	DEPTH LIMIT	TEMP. LIMIT	PRESS. LIMIT	RESOLUTION AND ACCURACY	OUTPUTS AND READOUT	CABLE REQ'TS	PURCHASE/ RENTAL COSTS	SERVICE LIFE
GYROSURVEYOR HUMPHREY (HORIZONTAL SURVEYOR)	DIRECTIONAL GYRO PENDULUM WITH POTENTIOMETER	1.38" DIA.	28V DC FROM 115V 60Hz SUPPLY	±60° INCL. ±45° AZIMUTH	1500 FT (1000 FT DIST. TO DATE)	250-300°F	15K PSI WITH 3/8" CASE	RES .1° INCL. ACC .1° INCL. GYRO DRIFT 4-6°/HR GOOD	OC VOLTAGES, SCANNED DIGITAL DISPLAY, PRINTOUT	4 COND.	PURCHASE $14K-$22K	400-500 HR GYRO BEARINGS
SURWEL SPERRY-SUN	GYROCOMPASS, PENDULUM	1-3/4" AND 3" DIA.	SELF-CONT. D CELLS 30V	0-2° TO 0-90° INCL. 360° AZIMUTH	23K FT	—	—	RES 5' INCL. ACC 6"/1000 FT GYRO DRIFT 1°-3°/HR GOOD	PHOTO-SINGLE SHOT	WIRE LINE	RENT SERV. 23¢/FT $920 MIN.	20 HRS IN HOLE
MAGNETIC MULTISHOT SPERRY-SUN	MAGNETIC COMPASS, PENDULUM	1-1/4" DIA. AND 1-3/4" D SHIELO	SELF-CONT. D CELLS 8-10V	0-2° TO 0-120° INCL. 360° AZIMUTH	—	600° FOR 5 HRS	—	RES 5' INCL. ACC. ~1/2° BEST FOR AZIMUTH	PHOTO-MULTISHOT	WIRE LINE	RENT 12¢/FT $420 MIN.	700-800 HR IN HOLE
SINGLE SHOT SPERRY-SUN	MAGNETIC COMPASS, PENDULUM	<1-3/4" DIA.	SELF-CONT. D CELLS 8-10V	—	>20K FT	~400°F	—	—	PHOTO-SINGLE SHOT	WIRE LINE		—
EYE SCIENTIFIC DRILLING CONTROLS	3 AXIS MAGNETOMETERS 3 AXIS ACCELEROMETERS	<1-3/4" DIA.	DC VOLTAGE	0-90° INCL. 360° AZIMUTH	>16K FT	>300°F	20K PSI.	RES .01° INCL. .01° AZIMUTH .01°/100' DOG LEG .01 FT	PRINTOUT INCL., AZ., DEPTHS (2) LATITUDE, E-W DEPART., DOG LEG SEV.	SINGLE CONO. (SHIELD GNO.)	RENT $980/8 HR AND WIRE LINE $280+4¢/FT	100 HR
TELEDRIFT DYNA-ORILL	PENOULUM ACOUSTIC PULSE OUTPUT	5" DIA.	NONE	10-1/2° INCL. 3-1/2° RANGE	>22K FT	—	—	RES 1/2°	ACOUSTIC PULSES: 1 PER 1/2° IN.	NONE	—	—
TELEORIENTER DYNA-DRILL	ROTATING COUNTERWEIGHT ACOUSTIC PULSE OUTPUT	5" OIA.	NONE	360° AZIMUTH	>22K FT	—	—	RES 20 TO 90°	ACOUSTIC PULSES: TOOL BIT WRT LO SIDE	NONE	—	—
GYROSCOPIC MULTISHOT EASTMAN	DIRECTIONAL GYRO PENDULUM	3-1/8" DIA.	SELF-CONT. O CELLS 31V	0-12° TO 0-70° INCL. 360° AZIMUTH	12K-26K FT	300°F FOR 3 HRS	—	RES 1/4° INCL (INTERP. TO 5') GYRO DRIFT <6°/HR	PHOTO	WIRE LINE	RENT SERV. 22¢/FT $895 MIN.	~3 MO MTB REPAIR

1 in. = 2.54 cm
1 ft. = 0.3048 m

$$t^{o}f = \frac{(t^{o}f - 32)}{1.8}{}^{o}C$$

1 PSI = 6.90 kN/m^2

Because of the above constraints, existing vertical borehole surveying equipment is inadequate for the proposed horizontal boring system. They are either incompatible with a continuous readout system or adequately miniaturized sensors have insufficient accuracy to meet navigation requirements. As a result, sensors must be examined individually.

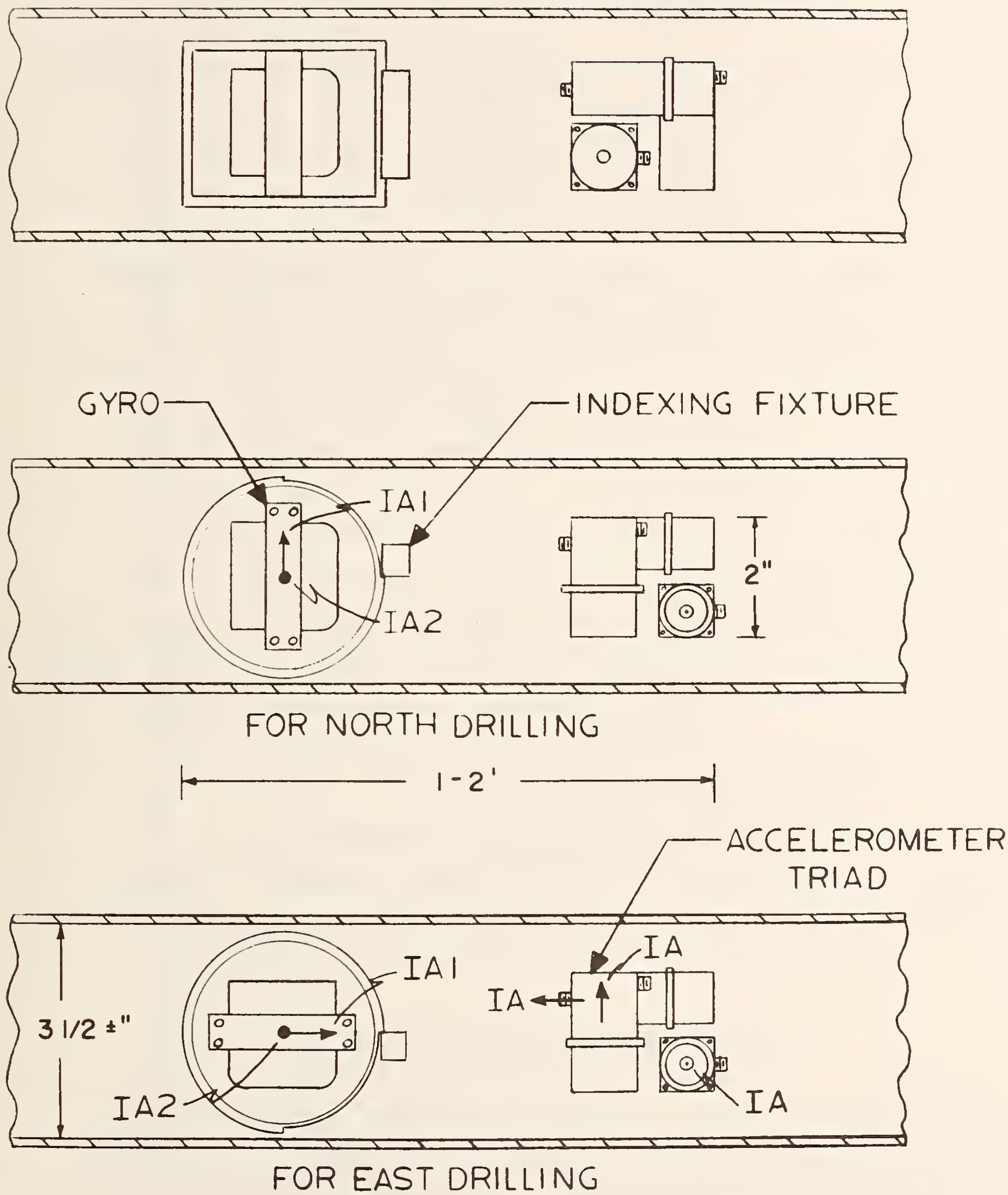
While basic accuracy might permit the use of magnetic devices for an azimuth reference having minimal performance requirements, they likely will be prohibited by the uncertainty of urban magnetic anomalies. See Appendix N for a case history describing the difficulties posed by magnetic anomalies. The only alternative instrument for a self-contained package is the gyro. Two-degree-of-freedom, flex-support designs offer good temperature sensitivity and require a minimum of units for unrestricted azimuth reference; as few as one gyro may be required if the instrument collar is nonrotating and a preferred roll orientation can be coarsely maintained. The shock and vibration specifications of these units should be adequate for the drilling environment. Some care in handling may be required because of angular velocity limits of the gyro torquers. Cost is in the vicinity of $15,000 per gyro with electronics.

Inexpensive accelerometers ($400 - $800) are available off the shelf. They can provide the required accuracy for determining drill elevation angle and gyro roll orientation. Their shock and vibration specifications should be acceptable.

The navigation canister presented in Figure 2.5 is the result of the above considerations. It is small, does not need to be updated but can be, meets the accuracy requirements and avoids the problems associated with magnetometers in the urban environment. It is a preliminary design and therefore will have to be further refined.

BIT COMMUNICATION

Trip time for surveying or tool adjustment is an expensive item in all drilling. In soft ground, non-penetration time is especially important because hole stability is dependent upon rapid penetration. An example of this dependence follows.



1 in. = 2.5 cm
1 ft = .304 m

FIGURE 2.5

INSTRUMENTATION CANISTER

(For nonrotating drill collars)

During the final phase of the Cerritos Channel Crossing (the first phase is described in Appendix N), the washover had to be stopped because of inadequate supplies of bentonite. Upon fresh supply the washover pipe could not be advanced (probably due to hole closure), and washover had to be completed from the opposite side.

For thruster systems, bit communication poses little problem because the surface is connected to the bit with a continuous cable. For all mandrel systems, rotating or stationary, continuous communication is currently impractical. A continuous cable, spooled at the surface, cannot be threaded through discontinuous pipe sections.

Table 2.5 summarizes the bit communication systems currently being developed. In addition EXXON has been investigating cable spools within drill string. There is but one telemetering system, TELCOM's, which has, to date, been delivered to the U.S.B.M., and it is not available on the open market. Numerous candidates are being developed by high-level internal funding programs by various companies. With the great need of these systems by offshore oil operations, it is anticipated that production systems will become available within a year. They may require some adaptation for the proposed horizontal boring system; however, these systems will have spinoff benefits for continuous communication with both mandrel and thruster penetration.

Only the Telcom system will permit data transmission at a rate which permits continuous sensing of geotechnical properties. However, this system involves drill steel which may interfere with geophysical sensing.

2.4 UP-HOLE CONFIGURATION OF EQUIPMENT

The equipment and space required for a compact surface operation is shown in Figure 2.6. If need be, the equipment could be contained in a space roughly equivalent to 5 to 6 contiguous semi-trailers. The following space modules (semi-trailers) are necessary:

Drill Carriage/Cable Reel	1
Cable and Steel Storage	1
Work	1

TABLE 2.5 CHARACTERISTICS OF ADVANCED BIT COMMUNICATION SYSTEMS

NAME & COMPANY	MECHANIZATION	CARRIER FREQUENCY	DIAM O.D. (in)	LENGTH (ft)	POWER	ACTUATION	BITS/SEC	LENGTH TESTED	INVEST TO DATE ($1000's)	RESTRICTIONS
CABLELESS TELEMETRY TELCOM	Electrical Current through Drill String	4050	3	6	Battery	Mud Pulse	15.0	1,500	200 (from U.S. government)	1)Fluid Around 2)Up Hole Direction Only 3)Signals Only When Stopped
EXTRA LOW FREQUENCY RAYTHEON	Electro-Magnetic Waves through Ground	20-25	6	20	Battery (100 Watts)	Surface Signal	0.2*	11,000 (Surface Down)	300 (Company Funds)	1)2000Ft Diam Antenna 2)Fluid Through 3)Repeators Every 6000 Ft. 4)12 in Diam Cased Hole*
TELECO RAYMOND PRECISION	Pressure Pulse through Drill Fluid	N.A.	7-3/4	34±	Down Hole Turbine	Mud Pulse	0.07	11,000	3,600 (Company Funds)	1)12 in. Diam Hole
CABLE NUMEROUS	Signal through Cable	N.A.	ANY	ANY	Through Cable	N.A.	ANY	N.A.	N.A.	1)Operate by Wire Line Or Employ Down Hole Thruster

* Without Casing Data Rate Increases to 10 BITS/SEC.

1 in. = 2.5 cm
1 ft = .304 m

Fluid Processing	1 to 2
Instrumentation and Control	1

Photographs and sketches of the necessary equipment are shown in the following Figures:

Drill Carriage	Figure 1.1
Fluid Processing	Figure F.8
Instrumentation	Figure E.8

Titan Contractors have mounted all necessary equipment on three 125 ft x 25 ft (38 m x 7.6 m) barges for a crossing of the Intercoastal Canal, Louisiana. Therefore for work in estuaries, the necessary equipment could be contained on four such barges.

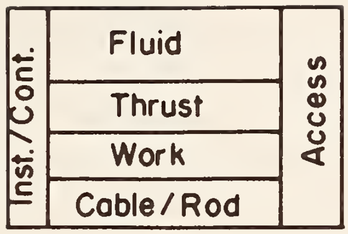
The mud processing equipment should be self-contained because of the difficulty in the disposal of the drilling fluid. Other research sponsored by D.O.T., "Hydraulic Transportation and Solids Separation of Excavated Materials in Tunnels," (Nelson, 1975) addresses disposal of fluids with large amounts of suspended solids. The storage requirements for recirculated fluids will increase as the length of hole increases. However, these storage units could be stacked.

In general, up-hole equipment configuration is a less restrictive constraint than the configuration of downhole equipment. Therefore, the selection process, described in Section 2.5, did not consider the configuration of up-hole equipment.

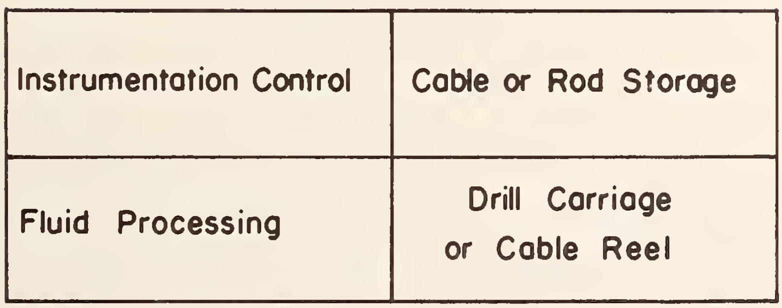
2.5 SELECTION OF TWO MOST TECHNICALLY FEASIBLE SYSTEMS

SELECTION PROCESS

In order to conserve the number of comparisons investigated, a number of constraints were not considered during selection. The cable design was only considered in so far as its outer diametrical requirements. Up-hole systems were not considered as these are not as space intensive as the in-hole systems. The navigation/survey system was miniaturized to a 3.5 in. (8.8 cm) diameter and did not enter consideration as it was slimmer than the smallest hole. Bit communication was assumed to travel via cable and drill steel for thruster and mandrel



a) IN URBAN AREAS - MINIMUM SPACE



b) ON WATER - 4 BARGES - MAXIMUM SPACE

FIGURE 2.6 UP-HOLE EQUIPMENT CONFIGURATION

respectively and is clearly better through cable. Therefore, it was not considered.

The constraints that were considered were primarily those of soil-mechanism interaction. First, four candidate systems (both thruster and mandrel) were selected that would best match the four predominant geologies. These systems are able to generate a minimum of 1000 lb (4.5 kN) allowed for the Dyna-Drill. These four systems were then compared numerically for three soil-mechanism interactions (jet erosion, shearing, return fluid hydro-fracture) and motor torque/volume. Only readily adaptable equipment was considered. The final systems, mandrel and thruster (shown in Figure 2.1) were then chosen. The resulting systems were further analyzed for their maneuverability and present and potential penetration distance.

GEOLOGICAL CONSIDERATIONS

For each one of the geologies considered in the design process, there are certain requirements or characteristics which must be fulfilled by the MPS selected. Therefore, the selection process will be geared to finding a particular combination of the previously mentioned feasible equipment which will meet the following requirements. Details of these considerations are contained in Appendix G.

The first condition considered is a loose sand or soft clay environment. The MPS selected for this subsurface soil condition must be mechanically simple to avoid sand-jamming of the anchor pads and bearing failure of deflection and/or anchor pads. The annular space available must also be sufficient to maintain laminar flow as much as possible. This will decrease erosion of the weak soils forming the borehole.

The next geological subsurface condition is a dense sand or stiff clay environment. In this subsurface soil condition, the pad bearing capacity is not as great a problem. However, the MPS should be designed to maximize the benefits of inhole thrusting. Therefore, the cable (or pipe) should minimize drag resistance. Here again, a sufficient annular size should be maintained to allow for laminar flow of

the drilling fluid. Erosion will not be as great, but cuttings may be larger.

The third geological condition is a residual soil or bouldery till Any MPS selected for this environment must be able to penetrate the large distribution of particle sizes one might encounter when drilling in these soils. Therefore, the minimum diameter of the MPS is an important parameter. The MPS must have the reserve torque available to bore through a large erratic boulder or core stone and be able to drill in a medium stiff clay. Obviously bit wear will be important in this environment.

The final condition, an urban environment, is not directly related to geology but is more concerned with avoiding encountered utilities and other subsurface objects. The subsurface soil conditions can be any one of the three previously mentioned environments. Therefore, the most important consideration for selecting a MPS for this condition is the mechanical flexibility and maneuverability of the system.

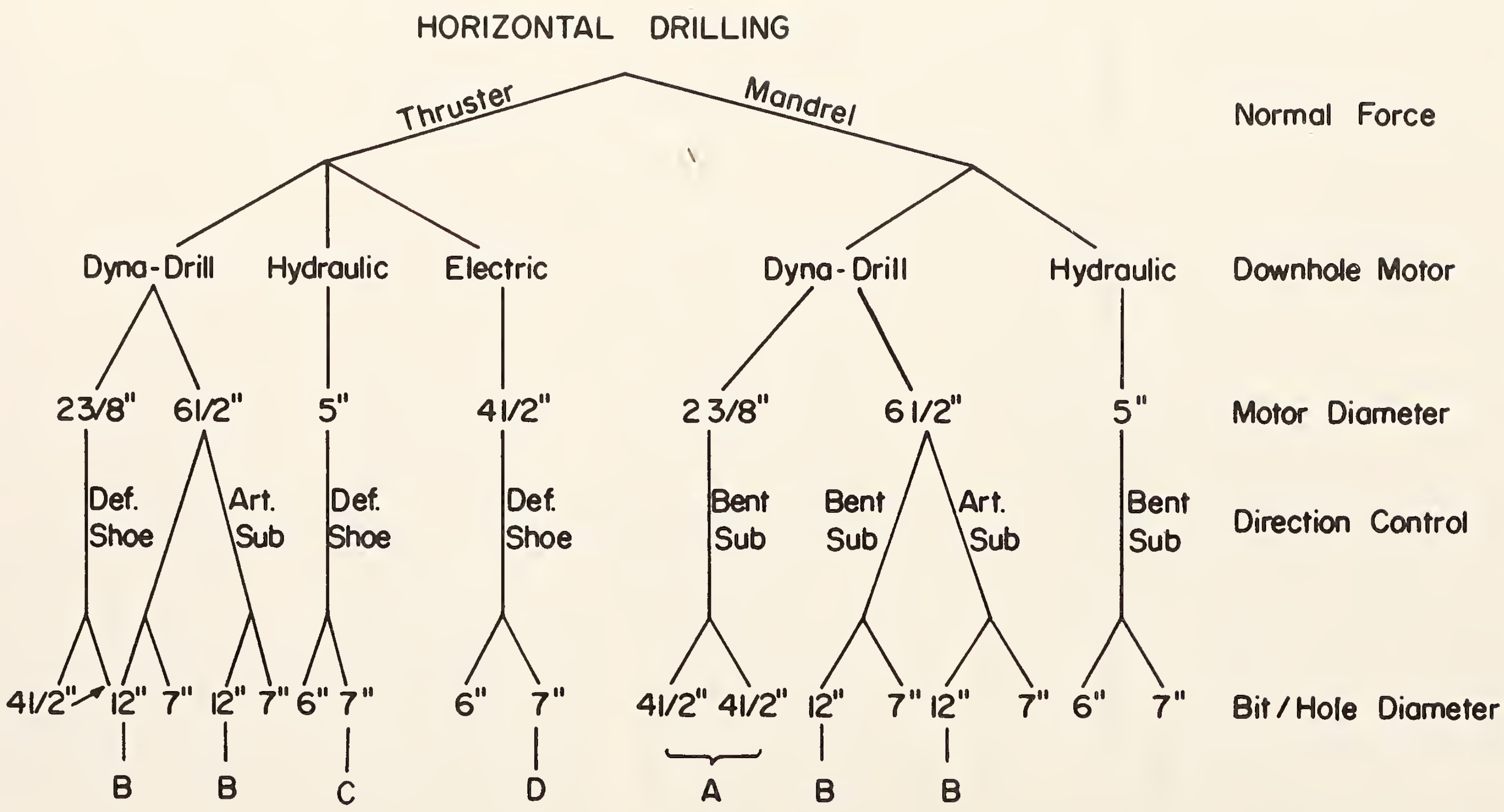
Figure 2.7 presents the possible combinations of the equipment that have been discussed, in a decision tree format. As can be seen, there are several alternative solutions for an MPS that will be operational in a horizontal hole in a particular geology. At this point maximum penetration distance will not be considered.

FINAL DESIGN SELECTIONS

The four final design selections (A, B, C, and D) are listed in Table 2.6. Each one of these systems has been chosen as being (1) more feasible to meet the penetration requirements, (2) representative of existing equipment, and (3) capable of operation in more than one geological environment.

The first MPS listed, A, is the 2 3/8 in. (5.4 cm) O.D. Dyna-Drill in combination with a bent sub or housing, 2 3/8 in. (5.4 cm) diameter drill pipe, and a diamond or drag bit (because of the high motor RPM). The torque output is high while the flow rate is relatively low, which is ideal for directional control.

The second MPS, B, is the 6 1/2 in. (16.5 cm) Dyna-Drill in combination with a bent or articulated sub, 4 1/2 in. (11.4 cm) diameter drill



1 in. = 2.5 cm

FIGURE 2.7 EQUIPMENT DECISION TREE

TABLE 2.6: DESIGN SELECTIONS

Selection	A	B	C	D
Drill Motor	Dyna-Drill	Dyna-Drill	Nichols Hydraulic Motor	Century Electric Motor
Drill Motor O.D. (in)	2 3/8	6 1/2	5	3 11/16
Length (ft)	8	19.6	4	4.5
Normal Force Device (NFD)	Mandrel	Thrust Appl. Mandrel	Thrust Appl.	Thrust Appl.
NFD O.D. (in)	2 3/8	8 (Thrust A.) 4 1/2 (Mandrel)	5 3/4 or 8	5 3/4 or 8
Direction Control	Bent Sub or Housing	Deflec. Shoe (Thrust Appl.) Bent S or H (Mandrel)	Deflec. Shoe	Deflec. Shoe
Bit Type	Diamond or Drag	Tricone	Tricone	Tricone
Hole Diameter (in)	4 1/2	12	7	7
Comments	Excellent annulus size, low flow rate, high torque	Maximum annulus size, maximum torque RPM, high flow rate can be a problem	Optimum annular space, short length, high torque low flow	Optimum annular space, minimum flow requirements, short length, problem with shorting

1 in. = 2.5 cm
1 ft = .304 m

pipe or an 8 in. (20.3 cm) O.D. thrust applicator, and a 12 in. (30.5 cm) diameter tricone bit. This MPS has been selected to be a heavy duty drilling system, applicable to a mixed soil with erratic pinnacles and boulders. Another reason for consideration of such a large diameter system is allowance for more space for geotechnical and geophysical equipment. Two normal force devices have been considered with this motor. If an 8 in. (20.3 cm) O.D. thruster is designed specially for soft ground conditions, then a thrust applicator might be used in soft clay soils that might also contain random pinnacles. However, the large system weight decreases its feasibility.

The next MPS, C, is the 5 in. (12.7 cm) O.D. W. H. Nichols hydraulic motor in combination with a modified 5 3/4 in. (14.6 cm) O.D. or redesigned 8 in. (20.3 cm) O.D. thrust applicator, deflection shoe, and tricone core bit. This MPS can easily operate in a stiff clay or dense sand formation; however, as previously stated, a redesign of the thrust applicator is required for operation in soft clay.

The final MPS, D, is the Century Electric motor in combination with either the 5 3/4 in. (14.6 cm) or the proposed redesigned 8 in. (20.3 cm) O.D. thrust applicator, deflection shoe, and a 7 in. (17.8 cm) diameter tricone core bit. This MPS can operate in the same geological conditions as selection C, but has the added ability of operating with all of its components being electrical (except for the CONOCO deflection shoe). This allows the drilling mud slurry to be employed strictly to clean the bit and stabilize the hole.

The electric motor-thrust applicator MPS might enable maintenance of just enough fluid flow at the bit to clean the drill bit teeth. The drilling fines would be carried past the thrust applicator and allowed to settle out around the thruster cable. Drilling fluid would not be recirculated for complete clean-out.

The advantage would be the elimination of a drilling fluid recirculation system. However, the disadvantage would be the reduction in travel distance due to an increase in the frictional resistance at the soil-hose interface. The actual calculations of this frictional effect have not been computed, however in this case, a neutrally buoyant

thruster hose would be a necessity to reduce frictional forces acting on the hose. The flow rate for the drilling fluid would be just enough to cool the electric motor, clean the bit and fill the hole with an easily penetratable viscous mixture of drilling slurry and fines.

Table 2.7 summarizes the MPS-geology compatibility relationship as related to the four final design selections.

Throughout this chapter, reference has been made to certain module spaces available with each MPS. One objective of the design method was isolation of certain spaces on each MPS which could be adapted for additional contact or geophysical instrumentation. Specific areas of possible module spaces can be seen in Figure 2.1. The following module spaces are possible depending on the hole sizes and configurations: (1) core of tricone coring bit; (2) deflection shoe pad; (3) anchor pads; (4) additional equipment packages between the orienting motor and drill motor; (5) area on the Dyna-Drill motor around the internal connecting joint; (6) instrument packages behind the thrust applicator or on cable; and (7) within the drill pipe.

NUMERICAL COMPARISON OF EXCAVATION ABILITY

Four parameters, discussed in detail in Appendices G and F, will be used to compare excavation ability of the four design selections. Three of the four parameters are dimensionless while the fourth is a ratio of the horsepower and the volume and the torque. The four parameters are the shearing, jetting, drill motor, and fluid system parameters.

The shearing parameter relates the undrained shear strength of the soil to the maximum rated torque of the drill motor. The jetting parameter is the ratio of the velocity necessary to erode soil divided by the drilling fluid velocity at the bit orifice. The fluid system parameter is the equivalent circulating density of the drilling fluid (bit pressure), divided by the hydraulic fracture gradient of the soil (fracture susceptibility). Finally, the drill motor parameter is the output horsepower of the motor divided by the volume of the motor divided by the rated output torque of that motor.

TABLE 2.7: MPS - GEOLOGY COMPATIBILITY

	Loose Sand Soft Clay	Dense Sand Stiff Clay	Residual Soil	Urban Environment
2 3/8 in O.D. Dyna-Drill with 2 3/8 in drill pipe	Yes^{o}	Yes	Yes$^{\Delta}$	Yes
6 1/2 in O.D. Dyna-Drill with 4 1/2 in drill pipe	No^{+}	Yes	Yes	No
5 in O.D. Nichols Hydraulic Motor with 5 3/4 in O.D. DRILCO Thrust Applicator	Yes*	Yes	No	Yes
4 1/2 in O.D. Century Electric Motor with 5 in O.D. casing and 5 3/4 in O.D. DRILCO Thrust Applicator	Yes*	Yes	No	Yes

1 in. = 2.5 cm

Remarks: Δ - With Diamond Bit

o - Must use Washover Pipe

* - Thrust Applicator Requires Redesign

+ - Due to Excessive Weight, See Appendices D and G

In addition, two other factors should be considered in the evaluation of the entire penetration system. Friction along the pipe or the cable will limit the penetration distance. Maneuverability will limit the system's adaptability to differing geologies. Both of those parameters entail mechanical system-soil interaction and are thus much less easy to model than the first four parameters. These aspects will be discussed after excavation abilities are compared.

Table 2.8 summarizes all of the calculations for estimating the four parameters describing excavation ability. Also included on this table is the most favorable condition or value for each particular parameter. The logic behind the "most favorable conditions" is summarized in the following paragraphs. More details are presented in Appendices G and F.

A shearing parameter greater than 1.0 indicates the motor will have difficulty drilling, if shearing at the outer edge of the bit is the predominant cutting mechanism for that particular bit (i.e., drag bit). Therefore, a drill bit with the least torque requirement (i.e. tricone bit) should be used with that particular motor. Any value less than 1.0 should provide good torque transfer efficiency for either one of the suggested drill bits.

The hydraulic motor and electric motor have the lowest shearing parameter for both soil strengths. Therefore, the rated torque output can easily shear the soil if that were the only mode of drilling the hole. The two values greater than 1.0 for the Dyna-Drill motor indicate that because of a lower rated torque output, they are best combined with bits that abrade rather than shear.

The larger the value of the jetting parameter, the less erosion will occur in front of the bits. Therefore, there is less chance of creating a large cavity at the drill face when the equipment advances slowly.

The hydraulic and electric motor both have a minimum jetting velocity, therefore, they will create the least amount of soil erosion at the bit face. Since the 6 1/2 in. (16.5 cm) O.D. Dyna-Drill has the highest flow rate, this drill motor will have the greatest erosive effect at the bit face.

TABLE 2.8 MPS COMPARISON PARAMETERS

	Shearing Parameter (SP)		Jetting Parameter (JP)		Drill Motor Parameter (DMP)	Fluid System Parameter (FSP)-			
						Clay		Sand	
						100 ft	500 ft	100 ft	500 ft
2-3/8 in D-D (4-1/2 in hole)	S_n=0.25 tsf 0.173	2.0 1.38	Sand 0.006	Clay 0.045	1018.5	1.08	.75	1.12	.78
6-1/2 in D-D (12 in hole)	0.210	1.68	0.002	0.014	14.6	0.76	0.71	0.73	0.68
Hydraulic Motor (7 in hole)	0.111	0.89	0.009	0.063	39.8	0.76	0.71	0.73	0.68
Electric Motor (7 in hole)	0.111	0.89	0.009	0.063	78.6	---	---	---	---
Most Favorable Condition	1.0 or less		larger value		smaller value	smaller value			
Formula	$SP=\frac{S_u \frac{d^3}{16}}{T}$		$JP=\frac{V_e(448)}{\frac{GPM}{A_{BO}}}$		$DMP=\frac{HP(550)}{\frac{Vol}{T}}$	$FSP=\frac{ECD}{HFG}$			

1 in. = 2.5 cm
1 ft = .304 m

The drill motor parameter is an indication of the maximum design efficiency of the drill motor. The smaller the ratio value, the more efficient the motor. The smaller number means that a high torque output is developed with a minimum amount of rated power for a given size hole.

The larger Dyna-Drill appears to have the most efficient usage of its volume and power rating to produce a specific amount of torque. This then is one of the reasons for selecting it to be the heavy-duty motor. It is interesting to note that the small diameter Dyna-Drill has a very high drill motor parameter, however, this is indirectly related to a low flow rate design which attempts to minimize the erosive jetting effects.

Finally, the fluid system parameter should be less than 1.0 because any number greater than 1.0 means the annular pressure is greater than the stress necessary to fracture the hole. Only the systems with the larger holes will have ratios less than one. This ratio is inversely proportional to depth for all systems. Therefore, at shallow depths, fracture is most likely, and the greatest problems will occur at entry and exit. Systems penetrating in sand will hydraulically fracture the most often. The Cerritos Channel crossing (Appendix N) offers a dramatic example of fracture in sand.

The development of these parameters permits analytical comparison of each MPS rather than subjective estimates of performance within a specific formation. The parameters presented are tools which should be employed to choose the drilling system which is most compatible with a particular formation. The performance parameters which are least amenable to analysis are presented in the following section.

SELECTION OF FINAL TWO SYSTEMS

Consideration of geologic adaptability and the four numerical comparisons lead to the selection of the system shown in Figure 2.1. It is essentially a basic thrust applicator with equipment discussed previously. By substituting the mandrel for the thrust applicator, there are two possible excavation systems. Only the bit communication

would be changed (cable to drill steel).

Figure 2.1 is not intended to be a working drawing, but instead illustrates the size compatibility of the various subsystem components. No intent has been made to duplicate manufacturers' drawings.

Maneuverability and maximum penetration capability of these two systems will be discussed in the following sections.

MANEUVERABILITY

Maneuverability is described in detail in Section 8 of Appendix G. It is dependent upon both the medium penetrated and the equipment penetrating. The parameter of importance is the minimum radius of curvature and build angle defined in Figure G.8. This parameter is an aggregate of (1) the bearing capacity of the deflection shoe and/or pad, (2) the deformability of the motor and/or thrust applicator, (3) the side cutting ability of the bit, (4) the hole diameter divided by the diameter of the stiffest element. This aggregation is simply not amenable to meaningful numerical analysis component by component without changing the scope of this report.

Therefore, maneuverability was approached on an empirical basis. The following three questions were posed and answered. What minimum radii of curvature have been observed in the field with thrust applicator and mandrel systems? Which elements control this maneuverability? Finally, what are the performance implications of a range of maneuverability covering present observations and most optimal expectations?

Observations were obtained in very soft materials (silty clay) with mandrel penetration and stiff material (soft coal) with thruster penetration. For soft ground with the mandrel system, continuous build angles are obtainable up to 12^{o}/100 ft with kinks up to 26^{o}/100 ft as indicated by Titan Contractors. For stiffer ground with thrusters, maximum build angles have been measured as high, 15^{o}/100 ft as indicated by CONOCO. Even through the mandrel has a larger observed kink, the thruster should be able to penetrate further with a kink because, keying (grooving of the hole at a kink) is less likely to occur with a cable than with drill pipe. However with either system kinked drill paths should be avoided.

There is yet another consideration for maneuverability. Is the real path circular or spiral? Only observations from continuous navigation systems can answer that question. These observations are not available. However, it seems likely that the path will be a spiral in softer materials and circular for stiffer materials for both systems. In addition, it seems likely that the mandrel's path would be circular only under ideal conditions.

The above considerations are summarized in Figures 2.8 and 2.9. These figures show the minimum detection distances required for objects of a given diameter as a function of path type; maximum allowable kink (for spiral paths) and constant build angle (for circular paths).

Even though the mandrel system can impose a kink of 26°/100 ft, it cannot continue to penetrate because of keying. Therefore, the most angular change one could expect with continued penetration is 9° to 12°/100 ft. On the other hand, the thruster is more capable of continued penetration at its maximum angular change. Therefore, it could tolerate an occasional 12° to 15°/100 ft change and continue, provided the cable continued to follow freely.

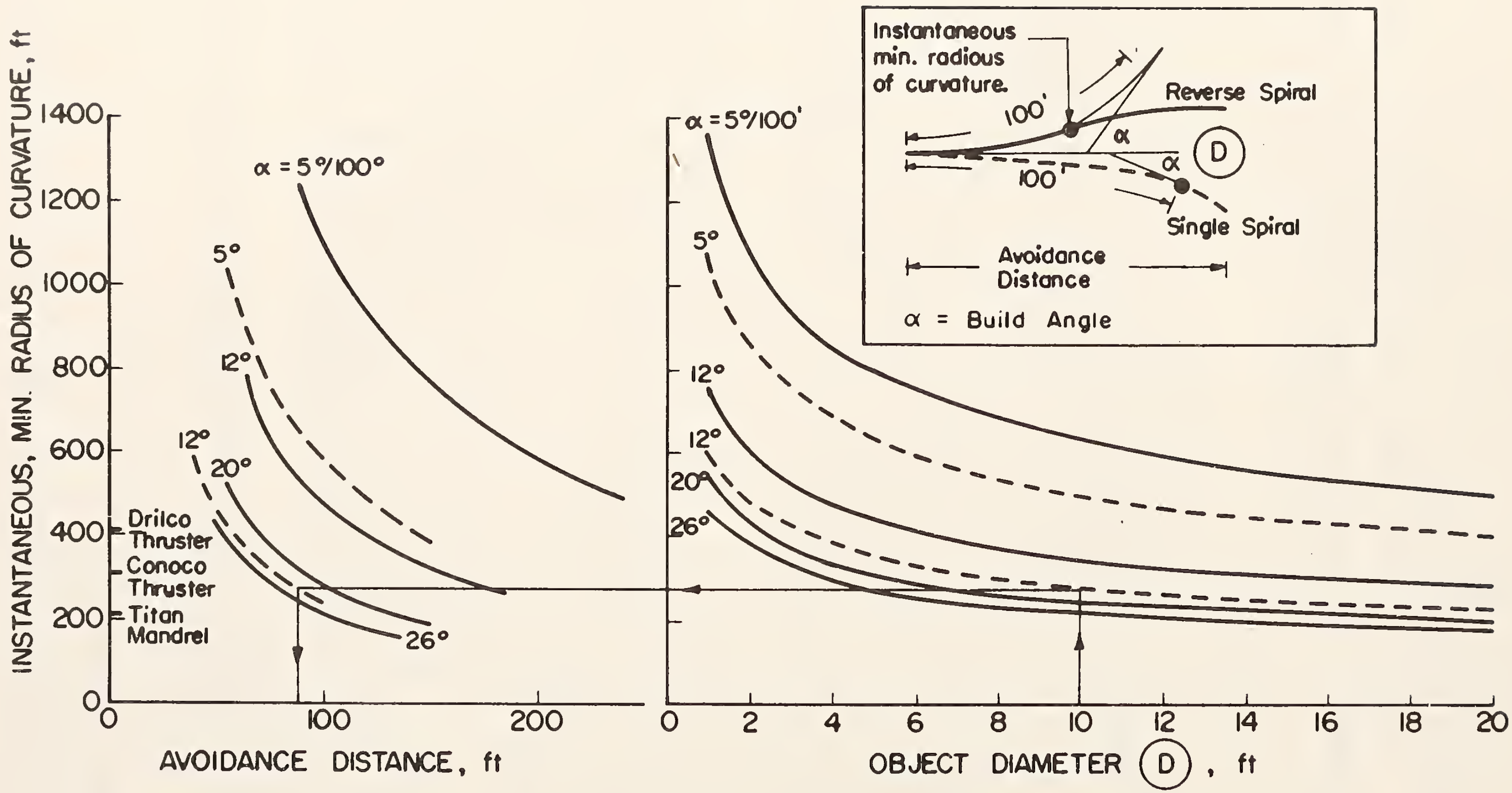
Further miniaturization of the thruster will permit increasingly larger build angles and still allow long penetrations. On the other hand, keying of the mandrel's drill steel will limit its maximum sustainable build angles. Maximum penetration distances will be discussed in the next section.

The depths and distance to horizontality are discussed in Section G.8. These are simply the geometrical result of the constraint of minimum radius of curvature. These plots allow preplanning of exploration routes. They include data for build angles from 5° to 26°/100 ft and will be useful even as future developments increase maximum sustainable build angles.

Chapter 3 compares optimum sensing distances and their relation to minimum radii of curvature.

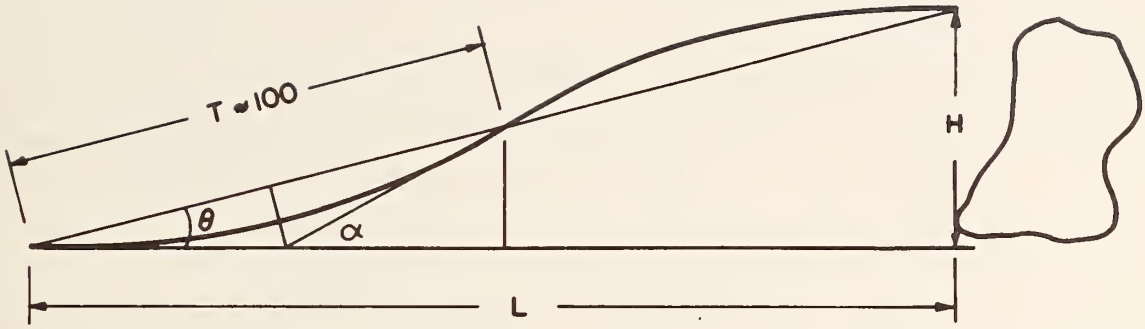
MAXIMUM PENETRATION DISTANCE

This discussion will focus on potential penetration distances for both the mandrel and thruster systems. Limitations of the mandrel



1 ft = .304 m

FIGURE 2.8 AVOIDANCE DISTANCE WITH SPIRAL PATH ASSUMPTIONS



α = Build angle/100 ft

T = Travel distance

L = Sighting distance = $H/\tan(\alpha/2)$

	α	L, ft (m)			
		H = 5		H = 10	
	5°	114	(35)	228	(70)
Continuous Optimum	9°	63	(19)	126	(38)
	15°	38	(12)	76	(24)
	20°	28	(8.5)	56	(17)
Kink	25°	22	(6.7)	44	(13)

FIGURE 2.9 AVOIDANCE DISTANCE WITH CIRCULAR PATH ASSUMPTIONS

system will be treated first. This discussion is based on material presented in Appendix G.

The three factors limiting mandrel penetration are pipe friction, buckling of the rod, and keying of the pipe at points of small radii of curvature along the drill path. Analytical treatment of the last two phenomena would require advances in analysis. Therefore they will be treated empirically.

Pipe friction was analyzed with typical B.Q. drill steel (2 3/8 in./6.0 cm O.D.). The frictional force would be approximately 2.21 lb/ft (39.1 N/m) when non-neutrally buoyant pipe is pulled over sand. This represents expected friction for a non-collapsed hole.

Out-hole buckling of the pipe was observed during the Cerritos Channel Crossing. Analysis of the case in Appendix G revealed that the normal force at the moment of buckling was 2.68 K (11.9 kN). Inhole buckling susceptability should be approximately this value.

Therefore the maximum penetration distance for a mandrel system would be

$$\frac{2.680\ \text{k}}{2.21\ \text{lb/ft}} = 1200\ \text{ft}\ (370\ \text{m})$$

provided the hole did not collapse. This observation is reasonable as Titan finds they must washover at distances of about 700 ft (210 m).

Titan has penetrated with their washover system up to 1685 ft (514 m) in the weak silty clays of the Atchafalya Basin in Louisiana. This marks their greatest penetration. They believe they could extend this distance to 3000 ft (910 m) with successive washover pipes in the Atchafalya Basin. However, the increasing diameter of the hole and amount of steel required for maximum penetration would interfere with sensing for all but a separate follower system.

The Atchafalya bore was made with a constant build angle of approximately 5°/100 ft. Therefore, Titan's distance records would be difficult to duplicate with paths with greater curvature because of keying of the pipe. The estimation of the keying force will require further investigation.

The four most important factors limiting thruster penetration in soft soil are (1) anchor pad traction or thrust development, (2) cable friction

and keying, (3) bit wear, and (4) hydraulic fracture. Thrust development and hydraulic fracture are the most important and will be discussed last.

The minimum frictional value would be the drag on a neutrally buoyant cable caused by the annular fluid flow out of the hole. Calculations in Appendix F reveal this minimum value with a 2 in. (5 cm) cable to be 0.01 to 0.11 lb/ft (.15 - 1.59 N/m) depending on the size hole.

Appendix D indicates that the maximum thrust presently available is 7,000 to 10,000 lbs (31.2 to 44.5 kN). This is <u>mechanically</u> available and is dependent upon anchor pad traction which, of course, is dependent upon soil shear strength. Therefore in stiff soil the maximum penetration distance would then be

$$\frac{10{,}000 \text{ lb}}{.1 \text{ lb/ft}} = 100{,}000 \text{ ft } (30{,}000 \text{ m})$$

This distance neglects cable keying around corners, bit wear, and transport of cuttings. Therefore it is overly optimistic but represents the potential of downhole thrusters.

CONOCO (Dahl, 1975) has been able to penetrate up to 800 ft (240 m) in soft coal with a downhole thruster. For soft coal excavation, the weakest link in the penetration system is the bit. The heel teeth of the tricone wear because of the pyrite inclusions. The tractive force of the thruster does not seem to be a problem.

In soft soils the reverse will be true. Tractive force will be the weakest link while bit wear will be minor except in erratic soils. Calculations in Appendix G indicate that the present 5 3/4 in. thruster would require 45 anchor pads to develop 1000 lb (4.45 kN) of normal force in soft clay (shearing strength Su = 0.25 tsf — 24 kN/m^2). Obviously, redesign of the anchor pad system is required. For instance, simple mechanical extensions of the present anchors to an 8 in. (20 cm) diameter would decrease the number of required pads by 2 for development of a 1000 lb (4.4 kN) normal force. With a 500 lb (2.2 kN) fractive force and a neutrally buoyant cable, the thruster would still be able to penetrate 5,000 ft (1,500 m) before fluid drag stopped penetration.

Head losses during return flow cause hydraulic fracture and would stop penetration before 5,000 ft (1,500 m) unless the equipment were

operating in overconsolidated clay or at depths below 200 - 300 ft (60 - 90 m) in sand. The interaction between return flow and penetration distances is discussed in Chapter 3. Details are presented in Appendix F. Essentially penetration would cease after hydraulic fracture because return flow would decrease. When return flow decreases, fluid velocity will decrease and cuttings will settle and jam the cable.

CHAPTER 3

EXPLORATION AND HOLE STABILITY

3.1 INTRODUCTION

CONTENTS

This chapter covers the stability of horizontal openings in soft ground, the disturbance around such openings, and contact sensing and geophysical exploration with horizontal boreholes.

Stability of horizontal openings in soft ground is treated in detail in Section 3.2, both in terms of theoretical solutions for stress distribution, and the interaction between excavation equipment, drilling mud and the soil. This task was undertaken to determine the potential of borehole collapse or erosion around the excavation device, and to assess the feasibility of pulling exploration instruments through previously excavated holes.

Soil disturbance around horizontal boreholes is analyzed with respect to the excavation methodologies and the stress change, and compared with the disturbance around vertical boreholes in Section 3.3.

The subsurface information desired for tunneling is identified in Section 3.4 and assigned to one of two distinct groups: (1) subsurface geometry and (2) soil and water parameters. Subsurface geometry denotes soil stratification, bedrock surface, presence of boulders or utilities and aquifer size. This information is mainly obtained by geophysical exploration. Soil and water parameters are typical geotechnical information such as soil strength, deformability, permeability, etc., and are mainly obtained by in situ-contact testing or laboratory tests on retrieved samples.

Available geophysical exploration methodologies, both from the surface and from boreholes, are discussed in Section 3.5. Suitable methods utilizing horizontal boreholes to gain information about the geometric or spacial distribution of subsurface materials and obstructions are

treated in detail. Special emphasis is placed on the physical limitations of equipment, i.e. their size and the compatibility with the borehole environment. Available attenuation data for seismic waves in soft ground have been collected from various sources and recast to determine distance-resolution relationships for possible equipment.

In situ-contact-testing equipment is described in Section 3.6. Suitable tools to obtain soil and water parameters for tunneling design (in horizontal boreholes) have been identified. Information resulting from the excavation process itself is also discussed, and incorporated in the overall exploration system.

STATE OF THE ART

Soft ground exploration for tunneling design utilizing horizontal boreholes is a fairly new concept. In rock tunneling, however, it is customary to drive exploration tunnels or pilot bores where the subsurface conditions are difficult to predict or construction problems are anticipated. Ash et al (1974) discussed the concept of horizontal boreholes as a part of the overall exploration effort prior to construction of soft ground tunnels. Existing equipment for vertical borehole exploration was examined in terms of adaptibility to horizontal boreholes. However, no specific equipment or packages were presented as part of an integrated horizontal borehole exploration system.

Stability of horizontal, mud-filled boreholes in soft ground has not been examined before. Soil disturbance around horizontal holes has been treated and compared with vertical hole disturbance.

The subsurface information required for tunneling design has often been described in publications (See e.g., Schmidt et al, 1974). This report presents a new grouping of the information, based upon parameter differences and the methods with which the parameters are explored.

The exploration systems described in the following (for horizontal boreholes) are based upon detailed knowledge of borehole stability, soil disturbance effects, measured attenuation of seismic waves, available space in the borehole and compatibility with the excavation equipment. Thus the conclusions are believed to be fundamentally correct, although

they are extrapolations and as such limited by the lack of field experience today--1975.

DESCRIPTION OF EXCAVATION DEVICE

Two basically different excavation systems have been presented in Chapter 2 which can provide the hole required for sensing. They are the Thruster, with a downhole thrust applicator and an umbilical cable as surface connections, and the Mandrel, with a non-rotating drillstring transferring thrust from the surface down to the drill bit. Chapter 2 and Appendices D, E, F, and G contain detailed information for the excavation equipment.

APPROACH TO INVESTIGATION

After initial background information was gathered, and the possible methodologies for soft ground exploration from horizontal boreholes were outlined, three important considerations became apparent.

First, size and compatibility of the exploration devices with the excavation system would rule out or demand redesign of most existing borehole sensing instruments. In addition, stopping the excavation to allow for sensing would cause substantial increases in the borehole excavation costs. These two major difficulties could all be overcome if separate "follower packages" for exploration could be pulled through a stable, excavated hole after removal of the excavation equipment. Therefore investigation of borehole stability is a prerequisite to the choice of the overall exploration method.

Secondly, disturbance of the soil around horizontal boreholes could lead to wrong or misleading conclusions concerning the soil parameters if they were measured in such a disturbed zone. Therefore, a knowledge of the size of the disturbed zone compared with the size of the zone sensed helped to determine the "best" sensing equipment.

Thirdly, feasibility of seismic exploration to detect obstructions in soft ground could not be determined without knowledge of seismic wave attenuation. Therefore, the investigation focused upon the determination of attenuation properties. Unconservative assumptions of

background noise and induced energy levels were made. Then maximum detection distances for given-sized objects were calculated. These calculations represent upper bounds of performance.

GUIDANCE TO THE READER

All information contained in this chapter is described in detail in Appendices F, H, I, J, and K. This chapter presents the summary, the conclusions and an overview of these Appendices. The chapter provides all essential findings and recommendations relating to exploration from horizontal holes. The reader interested in knowing "why" or "how" can consult the Appendices for the necessary background information, definitions and references.

3.2 STABILITY OF HORIZONTAL BOREHOLES

All aspects of horizontal borehole stability and interaction between excavation equipment, drilling mud and the in situ soil are discussed in detail in Appendices F and H which should be consulted for background information.

A successful drilling operation and the feasibility of follower packages for subsurface exploration are both dependent on the maintenance of the borehole integrity. The borehole wall must be kept from caving, and damage to the penetrated formations prevented. This necessary stability is attained by balancing the subsurface pressure with the drilling fluid at any time during and after the borehole excavation.

STRESS TRANSFER

Drilling mud pressure has to be transferred to the soil grains around the borehole as effective stress in order to support these grains. Dependent on the drilling mud characteristics and the soil permeability, the stress transferral occurs over a surface filtercake, via deep filtration or as rheological blocking. Figure 3.1 presents these three possibilities. An estimation of the drilling mud penetration depth can be obtained from Figure 3.2 Stability of single grains in the borehole wall

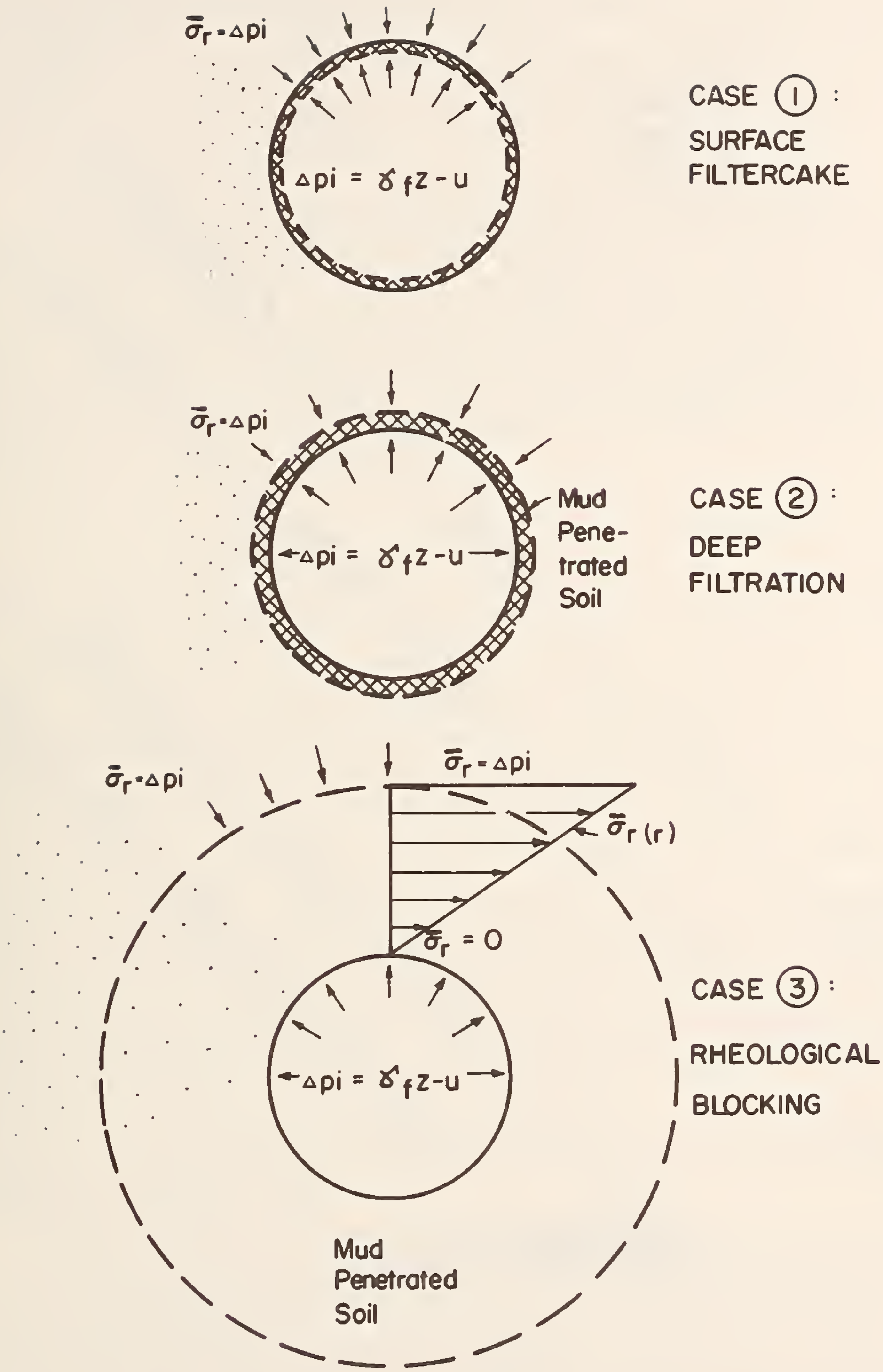


FIGURE 3.1 EQUILIBRIUM BETWEEN FORMATION AND DRILLING MUD PRESSURE

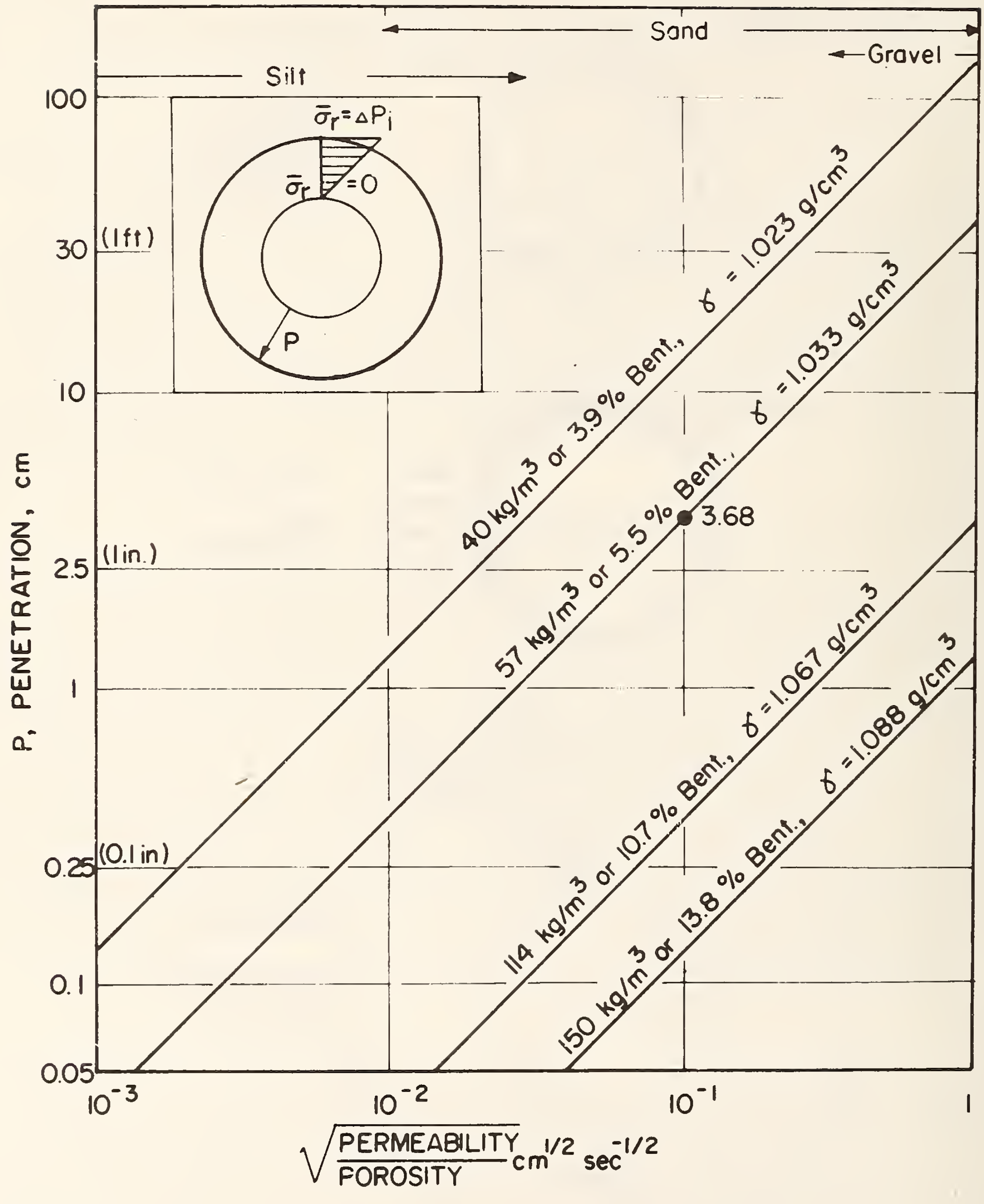


FIGURE 3.2 DRILLING MUD PENETRATION BY 14.4 PSI (1kg/cm^2) PRESSURE DIFFERENCE BETWEEN MUD AND POREWATER

and an effective stress transferral from the drilling mud to the soil around the borehole will always be ensured if the mud penetration does not exceed 1 in. (2.5 cm). Thus, open, pervious soil may be susceptible to stability problems unless a drilling mud with high bentonite concentration or additives is used.

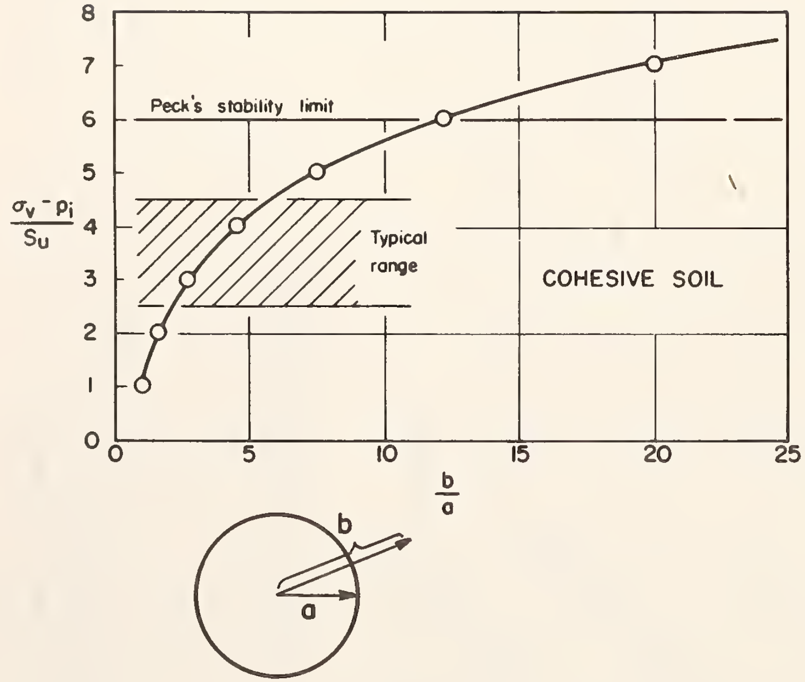
Single grain stability and effective stress transferral is not enough to ensure borehole stability. As previously noted, the mud pressure must be capable of balancing the subsurface formation pressure. Balance implies neither low internal hole pressure (which induces plastified or failed zones around the borehole) nor high pressure which hydraulically fractures the surrounding soil. Extent of the plastified zones will be presented first.

The theory of plasticity yields analytical solutions for the size of the plastic zone around horizontal openings in an ideal, homogeneous and isotropic medium where a hydrostatic state of stress exists (horizontal and vertical total stresses are equal in magnitude). In Figure 3.3, the plastic zone radius is cohesive soil (clay) and submerged cohesionless soil (sand) is plotted as a function of vertical stress, mud pressure and normally consolidated strength. The plastic zone radius is always finite, and for typical cases will range from 2 to 6 times the borehole radius in clay and from 1 to 3 times the borehole radius in submerged sand. In dry sand the plastic zone radius will be negligible. In summary, horizontal borehole stability is ensured, provided a suitable drilling mud (i.e., high enough bentonite concentration) is selected and the borehole is not located in extreme soft, cohesive soils or very open, pervious granular soils.

HYDRAULIC FRACTURE

If the drilling mud pressure exceeds a certain maximum, the soil around the borehole will be hydraulically fractured by the mud. The drilling mud pressure required to fracture the soil at a certain depth below the ground, divided by that depth, is known as the fractured gradient, Fg. In cohesionless soil:

$$Fg = \frac{1}{z} (u + K_o \bar{\sigma}_v)$$



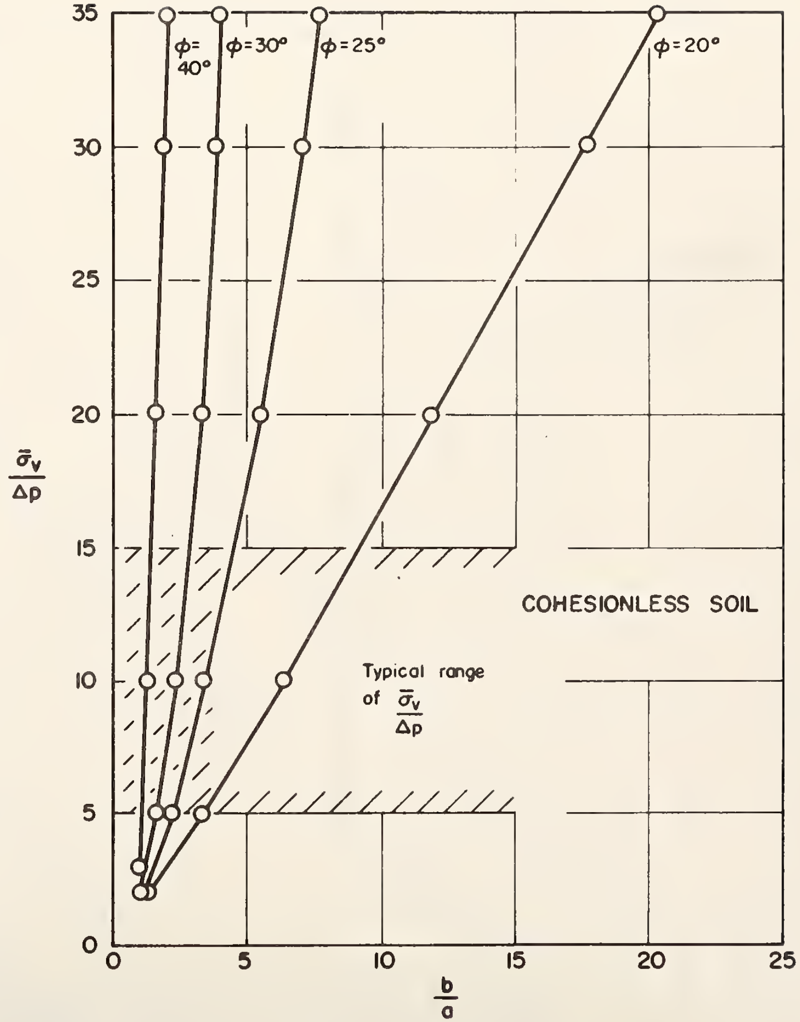


FIGURE 3.3
PLASTIC ZONE RADII
COHESIVE AND COHESIONLESS
SOILS

and in cohesive soil:

$$Fg \cong \frac{1}{z}\,(u + 2\,s_u + K_o\bar{\sigma}_v)$$

where: z = Depth below ground surface

u = Pore water pressure

K_o = Lateral stress ratio at rest

$\bar{\sigma}_v$ = Vertical effective stress

s_u = Undrained shear strength.

The existing drilling mud pressure in the borehole at any time is dependent on the mud's unit weight and the frictional resistance to mud flow in the borehole annulus and is called equivalent circulating density (ECD):

$$ECD = \gamma_f + \frac{\Delta P_a}{z}$$

where: γ_f = Mud unit weight

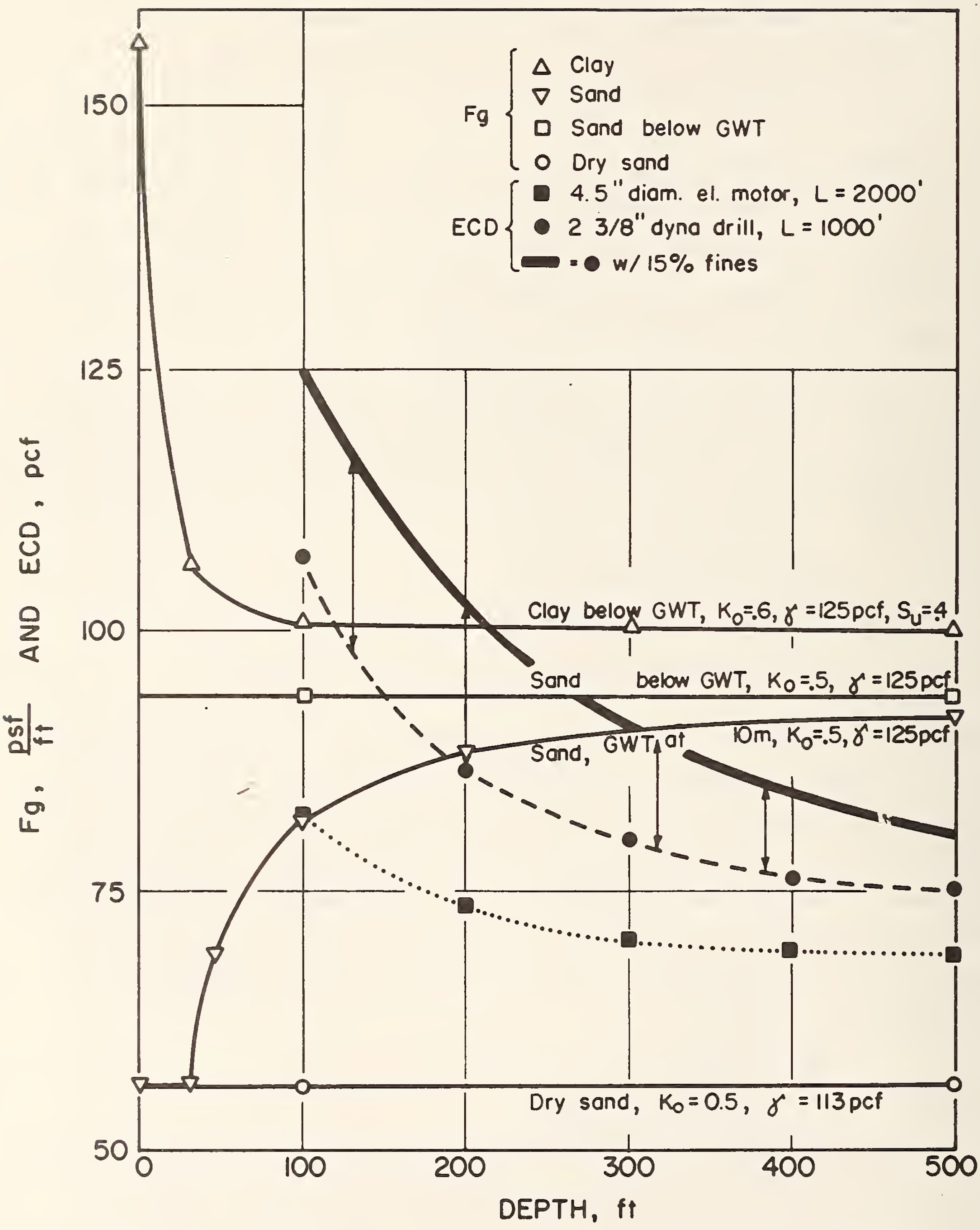
ΔP_a = Annular pressure loss from bit to collar.

The annular pressure loss is dependent on mud shear strength, borehole length, annulus size and mud flow rate. Figure 3.4 compares the fracture gradient and equivalent circulating density for a 5.5% bentonite-water mud with and without fines, for different soils and excavation systems. Whenever the equivalent circulating density exceeds the fracture gradient for a certain soil, hydraulic fracturing of the ground might occur. Calculations supporting Figure 3.4 are contained in Appendix F.

EROSION

Flow of drilling mud in the borehole annulus was found to be laminar for all considered excavation systems. Only at protrusions of equipment might the flow approach turbulent conditions. It is not likely that the laminar flow will cause erosion of the filter cake.

Sections F.3 and F.8, Annular Bit Pressure and Filter Cake Erosion, treat borehole wall erosion in detail. To date published research emphasizes erosion through turbulently flowing clear water. Return



(1 ft. = 0.3048 m)
(1 pcf = 16.01 kg/m^3)

(1 $\frac{psf}{ft.}$ = 16.0. kg/m^2/ m)

FIGURE 3.4: FRACTURE GRADIENT AND EQUIVALENT CIRCULATING DENSITY IN DIFFERENT SOILS AND FOR DIFFERENT EXCAVATION LENGTHS AND SYSTEMS

flow of the drilling mud involves laminarly flowing, bentonite slurry. Therefore reported test results are not directly applicable.

Special fan viscometer tests were performed for this project with slurry containing 15 and 30% (by weight) fines. Results were incorporated into ECD and erosion potential calculations. These tests were not modeled as well as they could be because of the scope of the project. Therefore, more precisely modeled tests should be performed.

If short term stability of boreholes in normally consolidated soils is ensured, long term stability will also be ensured due to soil strength increase with consolidation. In swelling clays the drilling mud might have to be replaced by an oil-based mud to prevent slow closure of the borehole. If large deformations or strength loss due to creep is anticipated, heavier drilling mud can be injected in the borehole after removal of the excavation equipment.

3.3 SOIL DISTURBANCE AROUND HORIZONTAL BOREHOLES

Appendix I presents a detailed discussion of soil disturbance around horizontal boreholes, and should be consulted for background information and definitions.

The mechanical action of the excavation equipment and the stress redistribution after the borehole is excavated will contribute to the disturbance of the soil surrounding the borehole. The disturbance will change the engineering properties of the soil, and subsequent measurements within this zone will not reveal the true in situ properties. Knowledge of the extent and nature of the disturbance is imperative to prevent misleading soil properties from being employed in subsequent tunnel design.

Based on theoretical treatment and the very limited experience available with equipment for horizontal borehole excavation, it was concluded that the mechanical action of the drill bit, the thruster pads, the deflection shoe and the drill string would not cause disturbance beyond one radius from the borehole wall. Hydraulic fracturing, excessive mud penetration in pervious soils, and mud jetting in front of the drill bit might lead to extensive disturbance. However, these latter three factors can probably be controlled.

Extent of soil disturbance resulting from stress redistribution around horizontal boreholes is assumed equal in size to the plastic zone developing around the hole. This is a conservative assumption. In Appendix H it is shown that in typical, normally consolidated, cohesive soils the radius of the plastic zone is 2 to 6 times the borehole radius, and in submerged cohesionless soils 1 to 3 times the opening radius. The horizontal and vertical stress are, however, not equal in magnitude, as assumed for calculation of the above values. From iterative elasto-plastic calculations, it can be deduced that the resulting plastified zone under different stresses will be as shown in Figure 3.5.

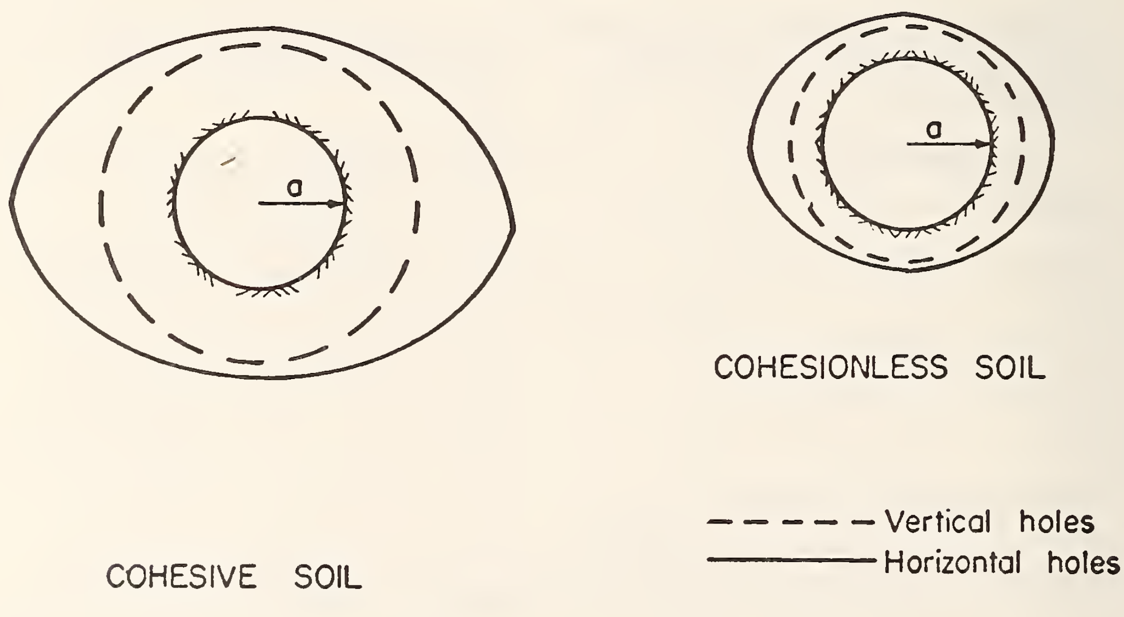


FIGURE 3.5 EXTENT OF PLASTIC ZONE AROUND HORIZONTAL AND VERTICAL BOREHOLES

A comparison of disturbance around horizontal and vertical boreholes is presented in Figure 3.5 for cohesive and cohesionless soils. Evidently the plastic zone is substantially larger around horizontal than vertical boreholes, and differently shaped. It is therefore unlikely that empirical correlations between measured values and the true in situ property from vertical borehole exploration can be applied unchanged to horizontal boreholes. A new set of indices will need to be developed. Only in front of the borehole face is the disturbance as small as one radius deep, and probably not very different from vertical boreholes.

Development of plastic zones will change pore pressure, strength and stress-strain characteristics of the plastified soils. No means exist today to backfigure the real in situ values. Therefore any soil exploration for undisturbed parameters will have to be performed outside the plastic zone, which will extend anywhere from 1 to 6 or more radii outside the borehole wall.

3.4 DESIRED SUBSURFACE INFORMATION FOR TUNNELING DESIGN

The soil parameters relevant to tunneling design can be divided into two major groups: geometry of the subsurface environment, and soil and water characteristics. This new grouping of the subsurface information is not only based upon the basic differences in the parameters, but also characterizes the method with which the parameters are obtained. Table 3.1 shows that geometry parameters are obtained mainly with geophysical exploration, whereas soil and water parameters are gained primarily by contact testing. The group "other" denotes exploration that cannot be performed from horizontal boreholes, such as visual inspection, vertical borings, etc.

3.5 EXPLORATION OF SUBSURFACE GEOMETRY

The geophysical methods available for subsurface exploration today (1975) are all listed and discussed in Appendix J. Of all geophysical approaches, seismic methods were found to be most promising for geometry exploration in soft ground, and had proven, on-shelf components to fit the size and compatibility constraints of horizontal boreholes.

GROUP	PARAMETER	EXPLORATION METHOD		
		Contact Testing	Geophysical	Other
GEOMETRY PARAMETERS	Stratigraphy		x	x
	Bedrock Surface		x	x
	Boulders		x	
	Utilities		x	x
	Aquifier Size & Recharge		x	x
SOIL AND WATER PARAMETERS	Soil Classification	x		x
	Permeability	x	x	
	Pore Pressure	x		
	Shear Strength	x		
	Consolidation Charac.	x		
	In-situ Stress	x		
	Poisson's Ratio	x	x	
	Young's Modulus	x	x	
	Shear Modulus	x	x	
	Time-Deformation Char.	x		
	Cohesion of Sands	x		
	Density	x	x	
	Relative Density	x		
	Water Content	x	x	x
	Water Chemistry			x
	Grain Size Distribution			x
	Plasticity Index			x
	Fissures			x

TABLE 3.1 SUBSURFACE PARAMETERS RELEVANT FOR TUNNELING DESIGN

Compared with seismic work in rock, exploration in soft ground appears limited. The main reason for this limitation is the high attenuation (damping) of seismic waves in soil. Table 3.2 presents available attenuation data for soft ground. These data, although incomplete, represent a large increase over that available only one year ago. More data should be available early in 1976. The P-wave data indicate a linear increase in decibel attenuation with frequency, so that a given soil will have a constant attenuation factor (amplitude loss in decibels/frequency and distance). This linearity in turn implies a linear decrease in the ability to see isolated objects (resolution) with distance. The resolution is linked to the wave length. The smallest detectable object is approximately one wavelength in diameter. Figure 3.6 presents the available attenuation data in terms of "minimum detectable boulder size" (resolution) versus distance from borehole. This plot is based on several assumptions, all listed in Appendix J. The effects of decreasing resolution are qualitatively shown in Figure 3.7.

The geometry exploration from horizontal boreholes can be divided into two phases: (1) exploration to avoid obstructions (e.g., boulders) during excavation of the horizontal borehole--denoted forward sensing; and (2) exploration for the design of the future tunnel--denoted all around sensing. Phase 1 will necessarily have to be performed during borehole excavation, whereas Phase 2 can also be performed after the borehole has been excavated. Figure 3.8 presents the geometry and definitions of terms regarding seismic exploration from horizontal boreholes.

FORWARD SENSING

Forward sensing from a borehole will have to be a reflection survey, as the wave transmitter and detector have to be placed close together. A spark device has been found to be a suitable transmitter as discussed in Appendix J; a small diameter air gun was also considered. The sparker delivers a sharp pulse over a wide frequency range with a short secondary oscillation. The sparker can be placed in a modular space on the drill bit with a detector on the motor housing as shown in Figure 3.9. The

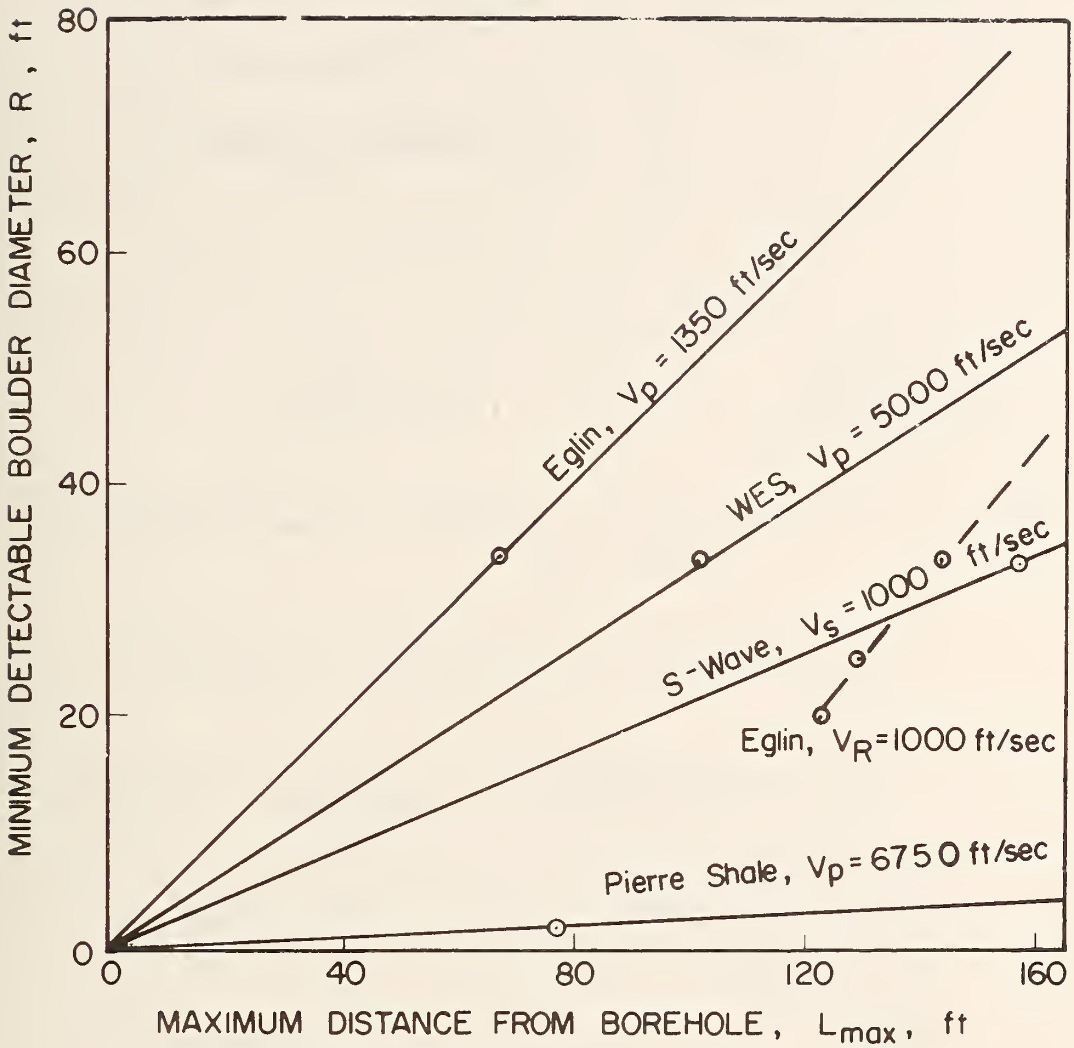
TABLE 3.2: ATTENUATION DATA

Test Description	Propagation Velocity V (ft/sec)	Attenuation** Factor k' (dB/ft·H_z)	Energy Loss (dB) Per Wavelength	Reference
Saturated soil, S-wave	2000	.0039	7.8	Brown (1974)
Wet soil, WES, P-wave	5000*	.0024	12	Weiss (1974)
Dry soil, Eglin, P-wave	1350	.0135	18	Weiss (1974)
Pierre shale, P-wave	6750*	.00012	.8	McDonald et al (1958)

* Estimated values

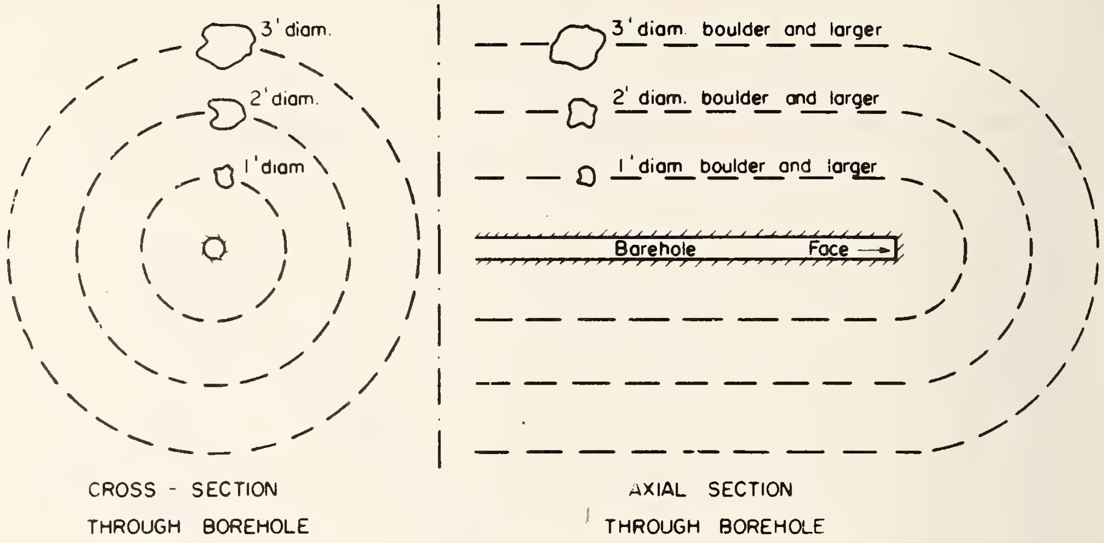
** The attenuation factor is a constant indicating how much wave energy is lost per unit distance and frequency.

1 ft = .304 m



1 ft = .304 m

FIGURE 3.6 MINIMUM DETECTABLE BOULDER SIZE VS. DISTANCE FROM BOREHOLE



1 ft = .304 m

FIGURE 3.7 QUALITATIVE CONTOURS OF DISTANCES TO MINIMUM DETECTABLE BOULDER SIZE

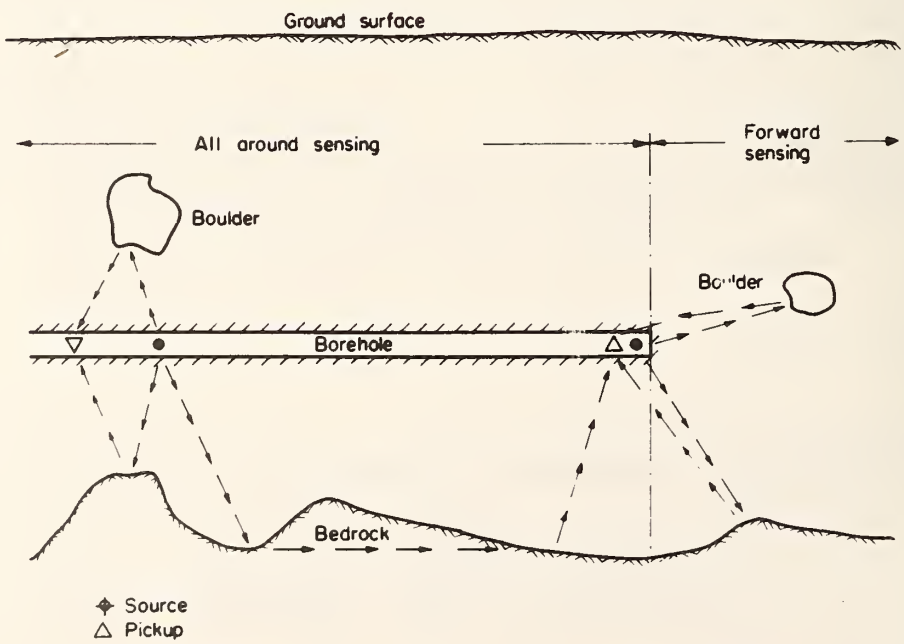


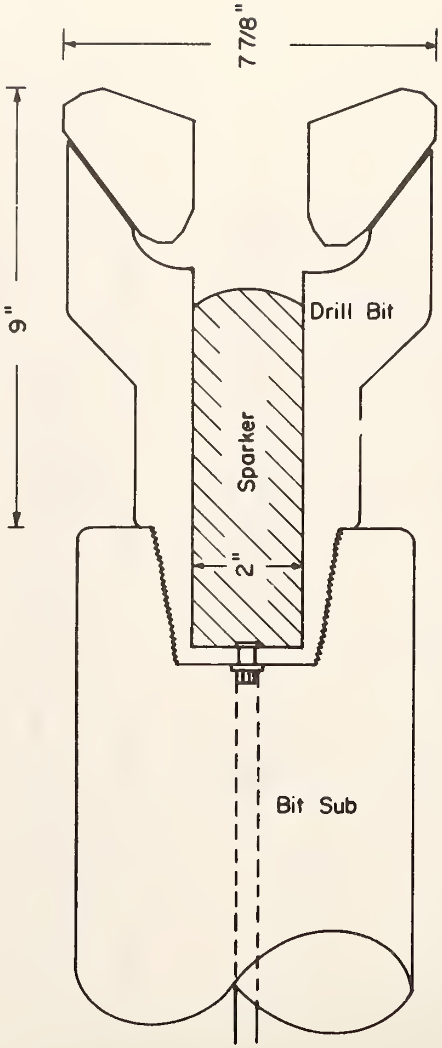
FIGURE 3.8 SEISMIC EXPLORATION FROM HORIZONTAL BOREHOLES (SCHEMATIC)

anticipated exploration capability of this sparker (called "snapper") in dry and saturated soil is indicated by the shaded area on Figure 3.9. Lack of low frequency waves limits the penetration in dry soil to 14 ft (4 m), which is virtually useless. In saturated soil the smallest detectable boulder diameter at a distance of 20 ft (6 m) is about 6 ft (2 m), and at a distance of 10 ft (3 m) it is about 3 ft (1 m). Thus sizeable boulders may remain undetected within the future tunnel volume, even though the exploration borehole is placed along the tunnel axis. In addition, the secondary oscillation of the source will mask reflections from objects closer than 6 ft (1.8 m). Table 3.3 compares maximum forward sensing distance to various size obstructions and the minimum travel distance to avoid the same obstructions. The travel distance has been calculated with spiral path assumptions and a range of possible build angles. Apparently no size obstruction can be detected in time for avoidance without backing up.

TABLE 3.3: COMPARISON BETWEEN MAXIMUM SENSING DISTANCE AND MINIMUM TRAVEL DISTANCE (SPIRAL PATH) ft (m)

OBSTRUCTION DIAMETER	MAXIMUM SENSING DISTANCE	MINIMUM TRAVEL DISTANCE (Build Angle/100 ft) (5^o)	(12^o)	(20^o)	(26^o)
1 (.3)	5 (1.5)	56 (17)	40 (12)	35 (11)	32 (10)
10 (3)	31 (9.5)	120 (37)	89 (27)	75 (23)	69 (21)
20 (6)	60 (18)	150 (46)	112 (34)	94 (29)	86 (26)

Above quoted limitations of the forward sensing system might not justify effort and money being spent on further development. However, the many assumptions involved, although selected to be unconservative, may prove conservative, and better sensing results than quoted may be achieved. The reflection survey will also yield information about the bedrock, and probably define irregularities better than a refraction survey.



1 in. = 2.5 cm
1 ft = .304 m

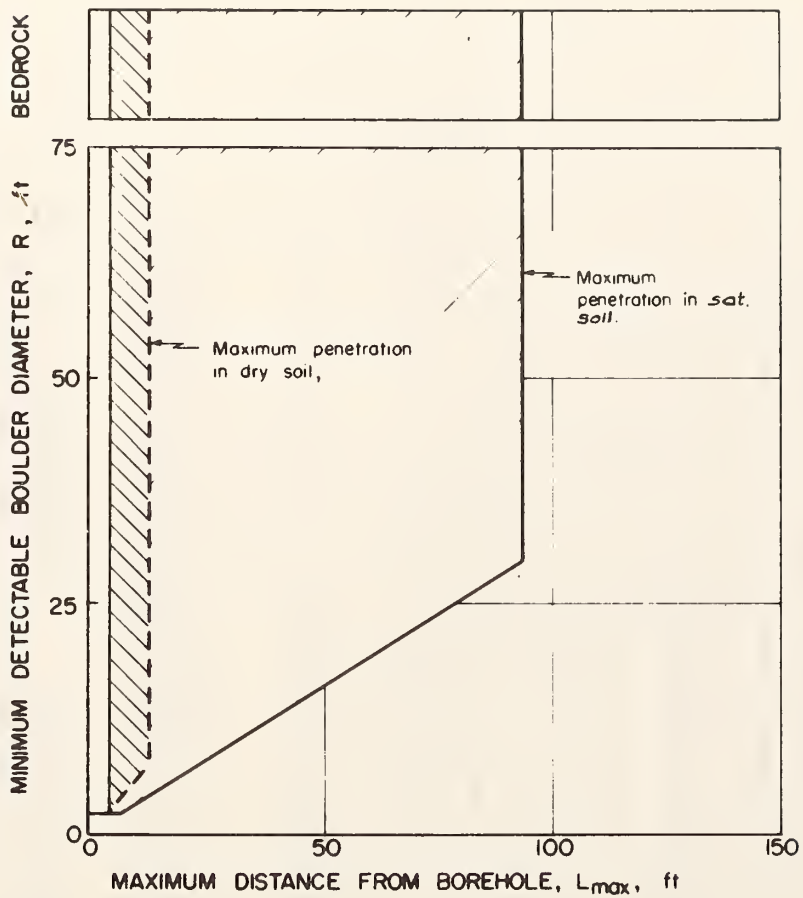


FIGURE 3.9 EXPLORATION CAPABILITY OF "SPARKER" AND PLACEMENT IN DRILL BIT

ALL AROUND SENSING

All around sensing to gain information about the distance to bedrock and wave velocities can best be achieved with a refraction survey assembly as presented in Figure 3.10. One air gun or sparker is placed at each end of a 200 ft (60 m) long streamer cable with 12 to 24 detectors. This assembly is not capable of detecting boulders. However, due to operation below surface velocity irregularities (fill and goundwater table variations) by the horizontal bore, the bedrock surface and blind zone (weathered rock) can be accurately mapped. See discussion of effectiveness in Appendix M. Attaching a sparker or an alternate device to the system could also enable reflection surveys.

In addition, a resistivity survey system could be configured in the same manner as the above refraction system. The electrode could be spaced along the cable or a follower package. In this configuration, resistivity equipment could be employed as an additional object evaluation tool where electrical resistivity or conductivity is of interest.

Other specialized follower packages for object evaluation could be pulled through a stable hole. The importance of hole stability was introduced in Section 3.2.

3.6 EXPLORATION FOR SOIL AND WATER PARAMETERS

This subject is discussed thoroughly in Appendix K, which should be consulted for background information and definitions.

Monitoring the performance of the excavation equipment will yield index information concerning the subsurface soil strata. Parameters such as penetration rate, type of cuttings, torque and normal force measured on the drill bit and load-deformation curves from the thruster's anchor pads can indicate soil "stiffness" and soil type. Due to the disturbance of the soil surrounding the borehole, the load-deformation curves will not yield actual strength of the in situ soil.

The contact testing device found most suitable and feasible to mount on the excavation equipment is the piezometer cone. Figure 3.11 shows the cone in the drill bit modular space, fully extended. Extension and thus soil penetration of the cone is facilitated by pressurizing the modular

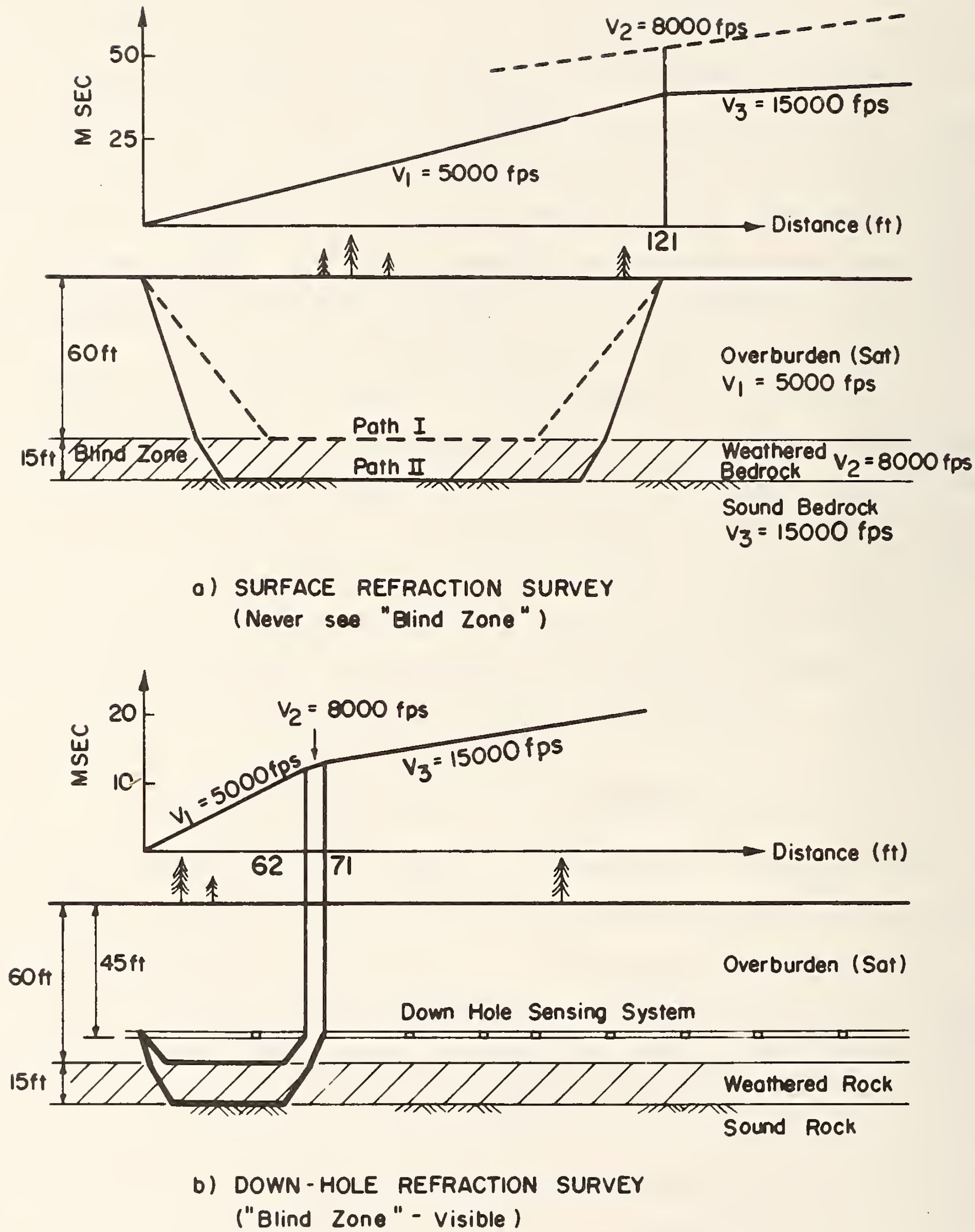
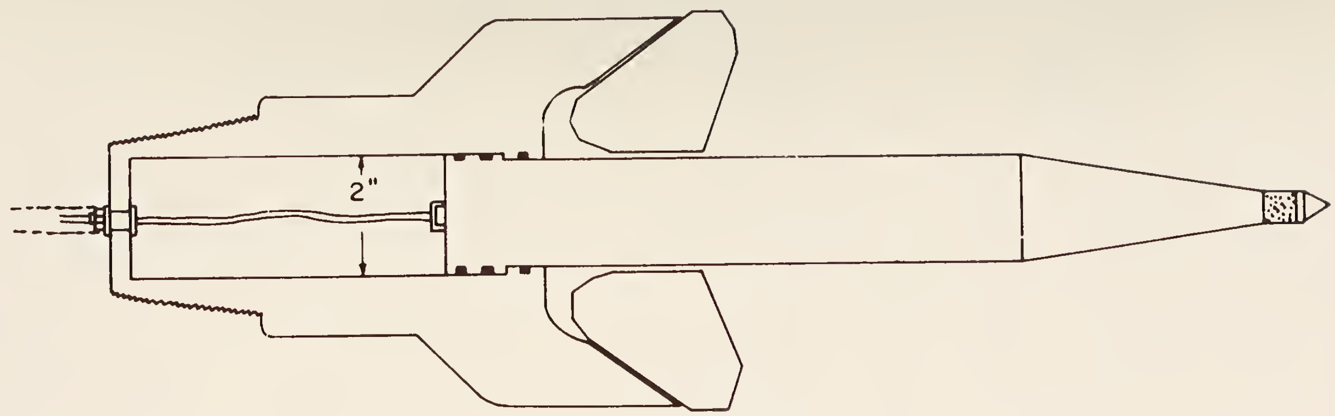
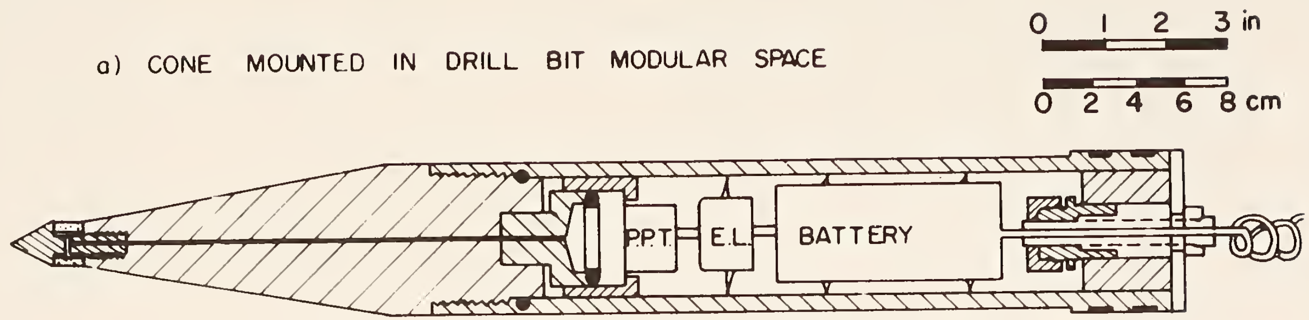


FIGURE 3.10 SURFACE AND DOWN-HOLE REFRACTION BLIND ZONE DETECTION

1 ft = .304 m



a) CONE MOUNTED IN DRILL BIT MODULAR SPACE



b) MODULAR SPACE ADAPTION

FIGURE 3.11
PIEZOMETER CONE CONFIGURATION

space with hydraulic fluid or drilling mud. Pore pressure variations and soil resistance are measured during penetration. Permeability and static pore pressure can also be measured, but require stopping at least 5 minutes and up to 3 hours, depending on the soil permeability.

Ensuring the stability of horizontal boreholes as discussed in Appendix H enables exploration packages to be pulled through the borehole after removal of the excavation equipment. Sidewall sampling, geophysical (electromagnetic nuclear response) logging, seismic reflection surveys, resistivity surveys, and caliper surveys are all feasible follower packages. The retrieved sidewall samples will be disturbed, but are well suited for index tests, soil classification, and remolded strength tests. The electromagnetic nuclear response logging may correlate with the soil permeability and may prove to be a tool for direct measurement of soil permeability with further testing. Two to four calipers can be placed at selected locations in the borehole, and the borehole deformations measured as a function of time with constant or decreasing mud pressure. Thus valuable information about the standup behavior of a subsequent tunnel can be obtained.

CHAPTER 4

VALUE AND COSTS OF HORIZONTAL EXPLORATION

4.1 SITUATIONS FOR HORIZONTAL EXPLORATION

To evaluate the horizontal exploration methods considered in this report, conditions most likely associated with soft ground tunneling in the next ten years in this country were projected. To develop these conditions, a list of cities which are considering transportation developments involving tunneling was obtained from the Transportation Systems Center (Van Dyke, 1972). These cities are listed in Table 4.1 along with the proposed tunnel lengths for both cut and cover and soft ground, the depth to rail, and the general geology and hydrology of the area.

In the next ten years some 215 miles (344 km) of urban rapid transit tunnels are being planned for construction or will be completed. Some 93 of those miles (149 km) will involve cut and covering or tunneling in soil. In addition, FHWA operating offices estimate that some 41 Lane miles (66 km) of soft ground highway tunnels are planned for the next 10 years; estimate includes cut and covering and immersed tubes as well as tunnels.

From Table 4.1 it can be seen that excavated soil will be predominantly glacial or residual; the transported soils of Los Angeles are the most extensive exception. Therefore, erratic boulders and core stones will consitute an important consideration. Except for St. Louis, San Francisco, and Los Angeles, the depth to groundwater is reportedly less than 50 ft (15 m). Therefore, exploration will be predominantly below the water table.

In addition to the two basic urban tunneling situations implied in Table 4.1 (beneath a river and on the horizontal), a third situation for soft ground tunneling is through a hill. Such hillside exploration is also applicable to portal exploration in colluvium for a rock tunnel. For each of these three basic situations, various geo-hydrologic conditions could exist. These are summarized in Figure 4.1.

Subsurface information desired for design of tunnels in the three

TABLE 4.1(a): CONFIGURATION OF PROPOSED RAPID TRANSIT TUNNELING
(future alternatives may include deeper tunnels)

City	Proposed Tunnel Lengths (Miles) Cut & Cover	Soft Ground	Total*	Depth to Rail (ft)	General Geology—Hydrology
Atlanta	3.0		3.0	≃ 35 ft	Silty SAND, clayey SILT; groundwater at 25 to 50 ft, weathered rock < 50 ft
Baltimore	5.0	3.8	8.8	25 to 100 ft	RESIDUAL SOIL and alluvial deposits generally above weathered bedrock; water table < 50 ft
Boston	2.0		2.0	≃ 60 ft	CLAY, stratified and unstratified glacial DRIFT; water table < 20 ft
Chicago	2.6	4.5	7.1	NA	Silty CLAY TILL; water table and bedrock depth vary widely
Detroit		9.2	9.2	NA	Glacial deposits--TILL, moraines, glacial--lake deposits; water table < 50 ft
Los Angeles		16.2	22.2	35 to 70 ft	Silty, clayey SAND with some boulders; groundwater generally < 25 ft but up to 50 ft
Minneapolis	0.8	1.0	7.0	NA	Stratified and unstratified glacial DRIFT; water table < 50 ft in most areas
New York			52	NA	Stratified and unstratified glacial DRIFT; bedrock and water table depth varies widely
Philadelphia	8.9		9.8	30 to 40 ft	Clay, silty CLAY, and mixed FILL material; groundwater 15 ft to 45 ft below surface, generally 30 ft
Pittsburgh		0.1	0.7	NA	Residual soils < 20 ft thick in most areas; water table depth varies widely
St. Louis		14.1	61.3	NA	Clayey residual soils, some LOESS and ALLUVIUM; bedrock and water table depth vary widely
San Francisco		3.7	4.1	≃ 50 ft	RESIDUAL SOIL, colluvium, alluvium, eolian, estuarine deposits, and till; bedrock and water table depth vary widely
Washington, D.C.	10.6	7.6	27.8	60 to 70 ft	RESIDUAL SOIL and alluvium; bedrock depth varies widely; water table depth generally < 50 ft

NA = Not Available

*For entire system including rock tunnels.

1 ft = .304 m, 1 mi = 1.6 km

TABLE 4.1(b): PLANNED[1] CUT AND COVER, SOFT GROUND AND IMMERSED TUBE HIGHWAY TUNNELS

State	Location	Length (Miles)[2]	Estimated Cost ($x10^6$\$) 75-85	Estimated Cost ($x10^6$\$) 85-95
California	Beverly Hills	4.2[2]		350
Connecticut	Hartford	.8	30	
Dist. of Columbia	South Leg	1.7	82	
	Center Leg	1.	30	
	Mall Master Plan	1.9		100
	Potomac River F'way	2.2	90	90
Florida	Miami	1.2		40
Illinois	Cook County	.8	35	
Louisiana	New Orleans	.5		20
Maryland	Fort McHenry	5.3	320	
	Fells Point	1.2		50
	Pratt St.	.4	12	
	Leakin Pk.	.4		20
Massachusetts	Boston Outer Harbor	2.6		160
	Fens	1.7	90	
Minnesota	Minneapolis	.6	25	
Nebraska	Omaha	.2	8	
New Jersey	Atlantic City	.4		18
	Elizabeth	1.2		40
New York	N.Y.C.	6.0		400
Pennsylvania	Philadelphia	.7	54	60
Utah	Salt Lake City	.4		20
Virginia	Hampton Roads	1.4	90	
	Craney Island	1.6	150	
	Norfolk	.3	18	
Washington	Seattle	1.2	90	
	Seattle	2.8		200
Wisconsin	Milwaukee	.6	25	

[1]Federal Aid Projects--Extimated by Office of Engineering, FHWA, 26 Nov., 1975

[2]Lane Feet divided by 2 x 5280 to estimate miles of tunnel.

1 ft = .304 m, 1 mi = 1.6 km

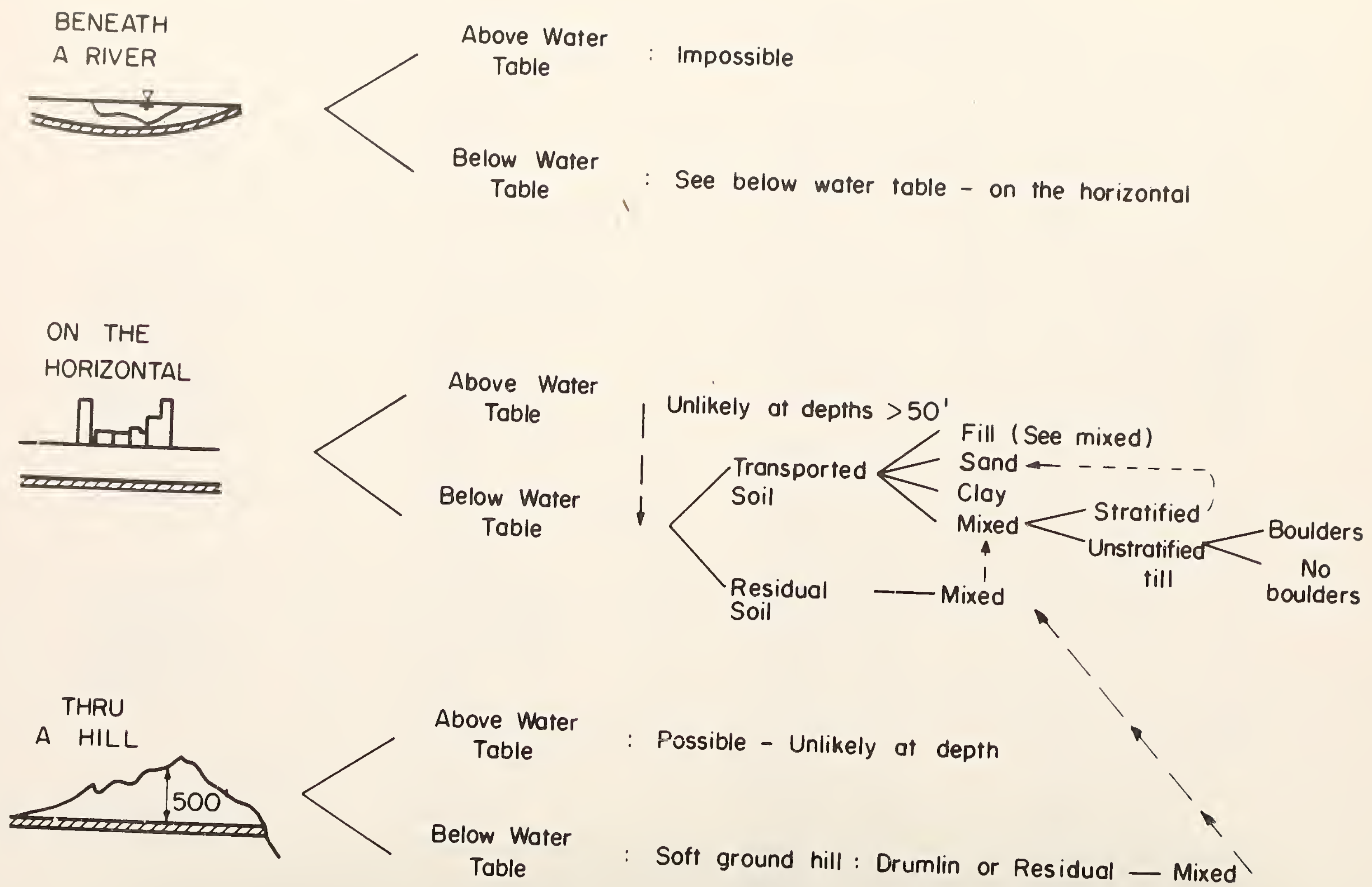


FIGURE 4.1 SITUATION CHART FOR SOFT GROUND TUNNELING

1 ft = .304 m

situations can be divided into two basic groups: subsurface geometry and water and soil parameters. Background for these groups can be found in Appendices J and K. Subsurface geometry denotes soil stratification, bedrock surface, presence of boulders or utilities and aquifer sizes. This information is mainly obtained through geophysical exploration. "Soil and water parameters" are typical geotechnical information such as soil strength, deformability and permeability and are obtained mainly by in situ contact sensing and testing of recovered samples.

Existence of subsurface obstructions in urban environs is almost a certainty considering geology and geography. These obstructions fall into two categories, namely boulders and utility lines. For boulders, determination of existance is important, as well as size and frequency of occurrence. For utility lines, determination of location is paramount to preventing any cutting or rupturing of such lines. Severance of utilities can occur during both exploration and tunnel construction. However, most small utilities will be within 25 ft (7.6 m) of the surface and only larger conduits would be found at depths where one would explore horizontally.

Running ground, as will be discussed later, is the most costly subsurface condition when it is unanticipated. Because of its economic importance, running ground will have to be identified no matter what approach is taken during exploration: horizontal, vertical and/or geophysical.

In general, what one hopes to achieve from an exploration program is a "best" prediction of the subsurface conditions and, hence, a minimization of the occurrence of unanticipated conditions while tunneling. Three unanticipated conditions were chosen for intensive economic analysis. In order of decreasing economic importance they are: running ground (geo-hydrological conditions), boulders and utilities.

Two exploration approaches which aid subsurface prediction will be compared economically. They are: surface methods and horizontal penetration methods. Surface methods were further subdivided into

vertical boring and surface geophysics. Horizontal penetration was subdivided by penetration method (mandrel and thrust applicator) and location of sensors (on board and independent follower).

4.2 COST OF UNANTICIPATED CONDITIONS

Two sources of tunnel cost data were found, from which cost increases resulting from unanticipated conditions could be estimated. One source was a sensitivity analysis of a soft ground tunnel cost model (Bechtel, A. D. Little, 1974), and the other a collection of individual case studies (Schmidt, et al, 1974). The methodology of data analysis and presentation is shown in Figure 4.2. It involved constructing several relations between tunnel excavation cost and ground conditions, and then verifying those relations with case studies. APPENDIX L CONTAINS DETAILS OF THE FOLLOWING SUMMARY.

First the case study data was translated to the value of a dollar in Chicago at the beginning of 1974. This transformation eliminated annual and geographic variation in dollar value, with the latter factor involving less than a $\pm 10\%$ correction.

The second step involved an assessment of the physical variables which are the primary source of cost increases, as well as the work item(s) which is (are) most seriously affected by these factors. A majority of cost increases in soft ground tunneling are caused by running ground (associated with large water inflow), boulders or various man-made obstructions occurring at unexpected locations or in unexpected severity. A brief analysis in Appendix L shows that these factors primarily influenced the excavation cost, which is the crucial determinant of the total tunneling cost (Schmidt et al, 1974).

The influence of excavation can be seen more clearly by examining Tables L.1 and L.2 of Appendix L. The two major work events in tunneling are excavation and liner - grouting; the latter can be broken down further into liner erection-caulking, grouting and tunnel liner cost (Tables L.3 and L.4). Of the second grouping, the tunnel liner itself constitutes 65% to 70%, and remains constant even under changing groundwater conditions (evidenced by the change from free-air to

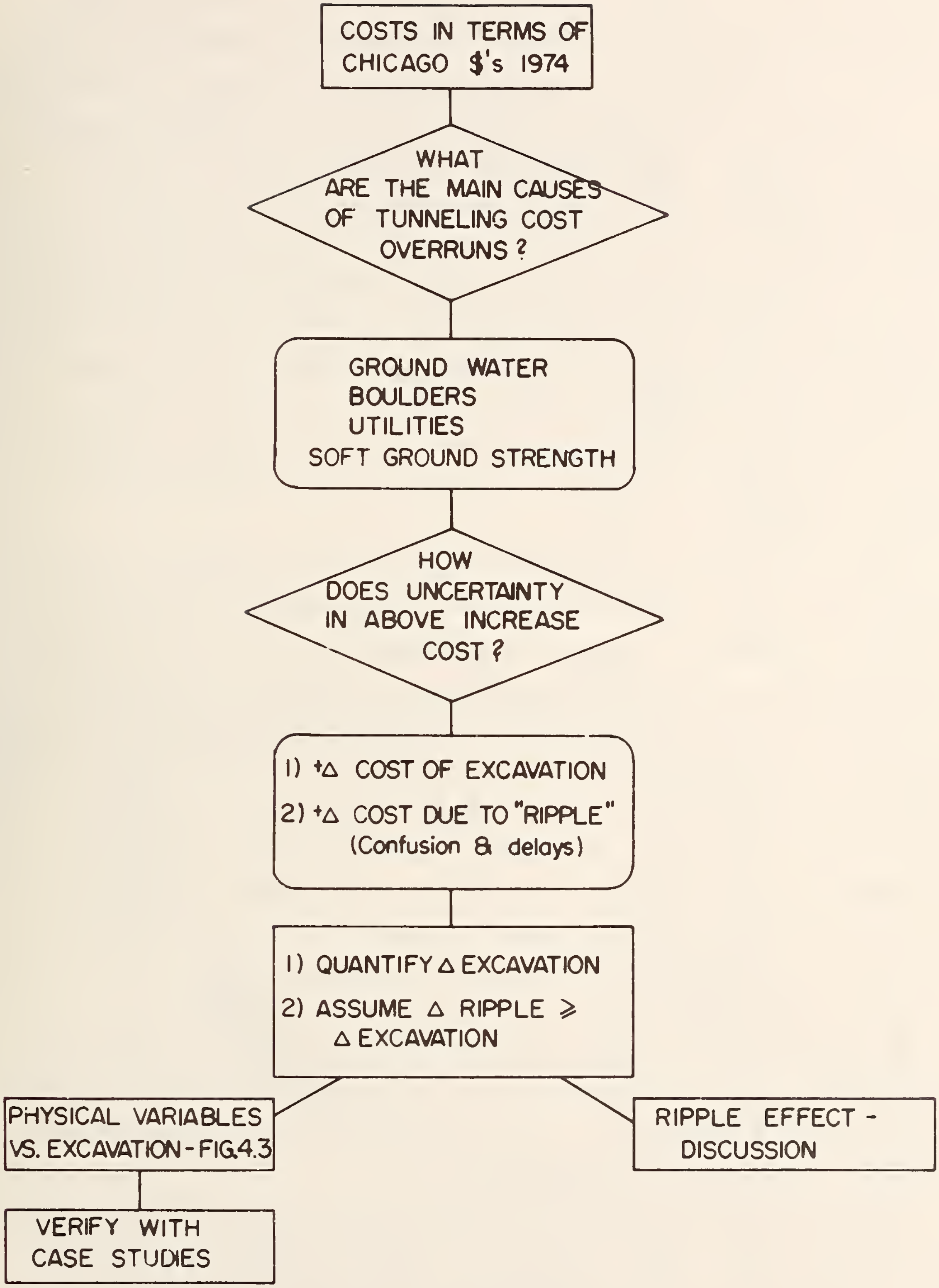


FIGURE 4.2 METHODOLOGY : VALUE OF SUBSURFACE INFORMATION

compressed air). The same groundwater change causes a 47.5% increase in excavation cost. This fact further emphasizes the importance of excavation cost, i.e., it is very sensitive to changes in subsurface conditions.

The effects of variations in groundwater inflow, boulder frequency and utility density on excavation cost were derived from the data in Tables L.1 and L.2 in Appendix L and are summarized in Figure 4.3. Refer to Appendix L for a detailed description of the method of construction. Also shown in Figure 4.3 are the Base Excavation Cost (BEC) and several points from separate case studies. The BEC is the cost of excavation under conditions of low adversity, i.e., when the three chosen physical variables have a minor effect on cost. Individual points represent data from various case studies and serve to check the trends derived from Tables L.1 and L.2. These cases are also discussed in detail in Appendix L.

Figure 4.3 provides a conservative estimate of excavation cost increase which is also a conservative estimate of potential savings (See Appendix L, Section 6). The lack of extensive case study data prevents a more conclusive statement on the validity of Figure 4.3 from being made. Another complicating factor is the subjective judgment required to assess the level of adversity of the physical variables. These qualifications become minor, however, when considering the overall value analysis. Assessing the probability that a physical variable will occur at a given level of adversity a certain number of times in future tunnel construction, is subject to more uncertainty than the estimate of potential savings for any particular event.

Changes in excavation cost are indices of the true project savings resulting from avoiding cost increases with adequate subsurface investigation. The true savings are the differences in total costs which result from the elimination of institutional confusion and time delays. An example can help clarify this point.

If a contractor had known of an unfavorable condition beforehand, his bid would rise an amount close to the excavation cost increase. Thus estimated project costs can increase with better subsurface information. However, the total cost increase with adequate subsurface information will not be as great as that without adequate information

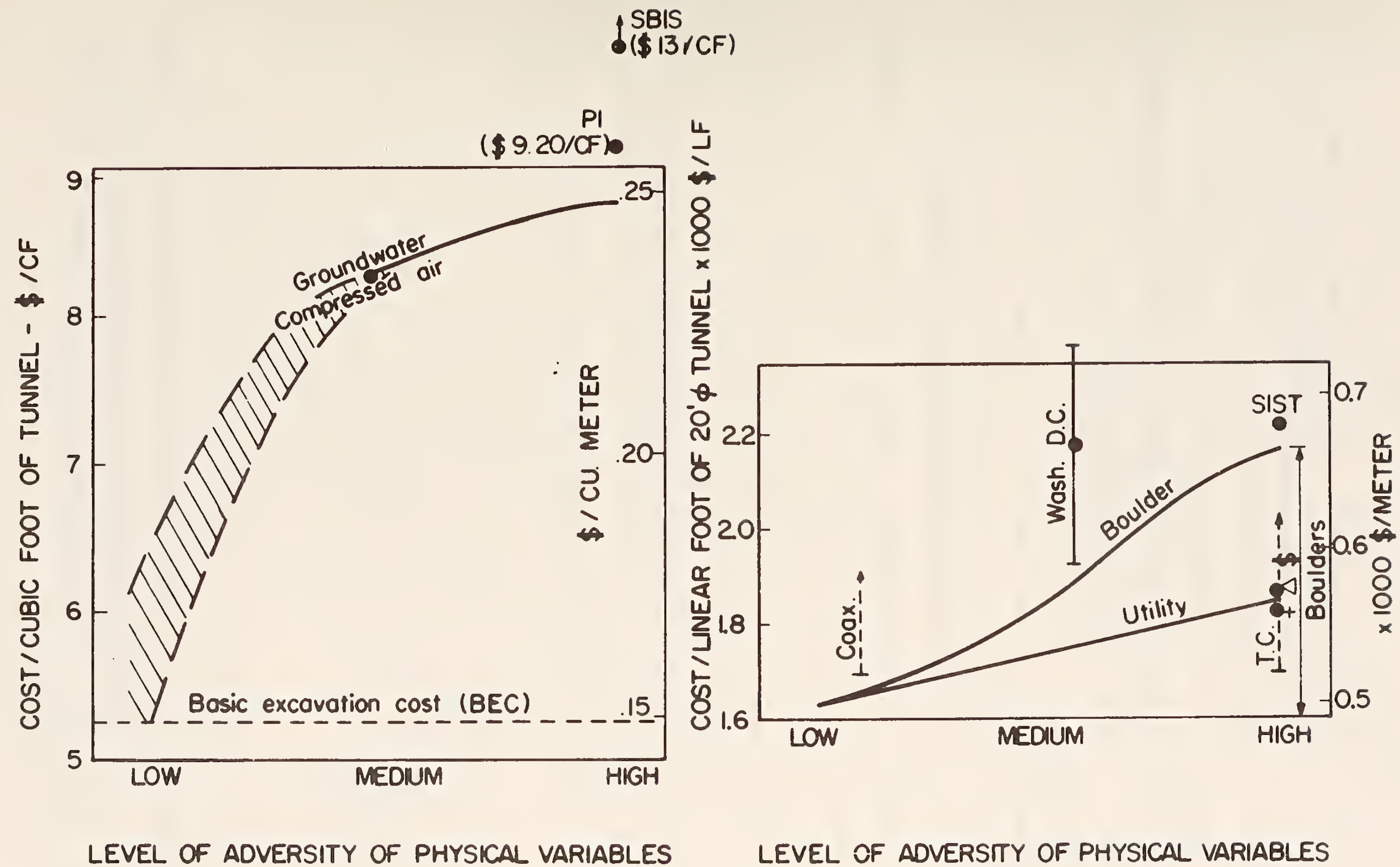


FIGURE 4.3 EXCAVATION COST INCREASE DUE TO ADVERSE PHYSICAL VARIABLES

because of the elimination of institutional confusion. The institutional factors affecting construction are given in Tables L.1 and L.2.

Figure 4.4 schematically illustrates the institutional concept described above. Since actual savings will never be known, they will be assumed to equal the potential savings. The potential savings is not necessarily the difference between excavation costs $(E_P-E_B)_{UNKN}$ approximated (E_P-E_B). Therefore, even though differences in excavation costs are not necessarily the same as total project cost differences, excavation cost differences are a good index for total project cost differences.

The greatest savings of all can be realized by switching routes so that excavation techniques will not need to be changed. In this case the comparable potential savings is even larger than that with the same route since both increased excavation and institutional confusion costs can be avoided. Herein lies the greatest reason for performing intensive subsurface investigation. To take advantage of this potential savings, investigation must be carried out before routes are locked in place.

A study of seven tunnels driven through the Continental Divide in Colorado (Dowding and Miller, 1975) indicated that less than 50% of the location decisions were based on geology. Since these tunnels were excavated in remote areas, route locations for urban tunnels would be expected to be even more heavily influenced by systems and policy constraints.

In general, then, Figure 4.3 and its supporting cases represent a lower bound of cost savings resulting from accurately predicting subsurface conditions. The difference between the cost increases and the BEC is the potential marginal value of accurately predicting subsurface conditions (MV).

4.3 COSTS AND CONSIDERATIONS FOR SURFACE EXPLORATION METHODS

Currently available surface techniques for exploration are vertical borings and surface geophysics. Costs and considerations were developed for each and are summarized in the following sections. Details of these analyses are found in Appendix M.

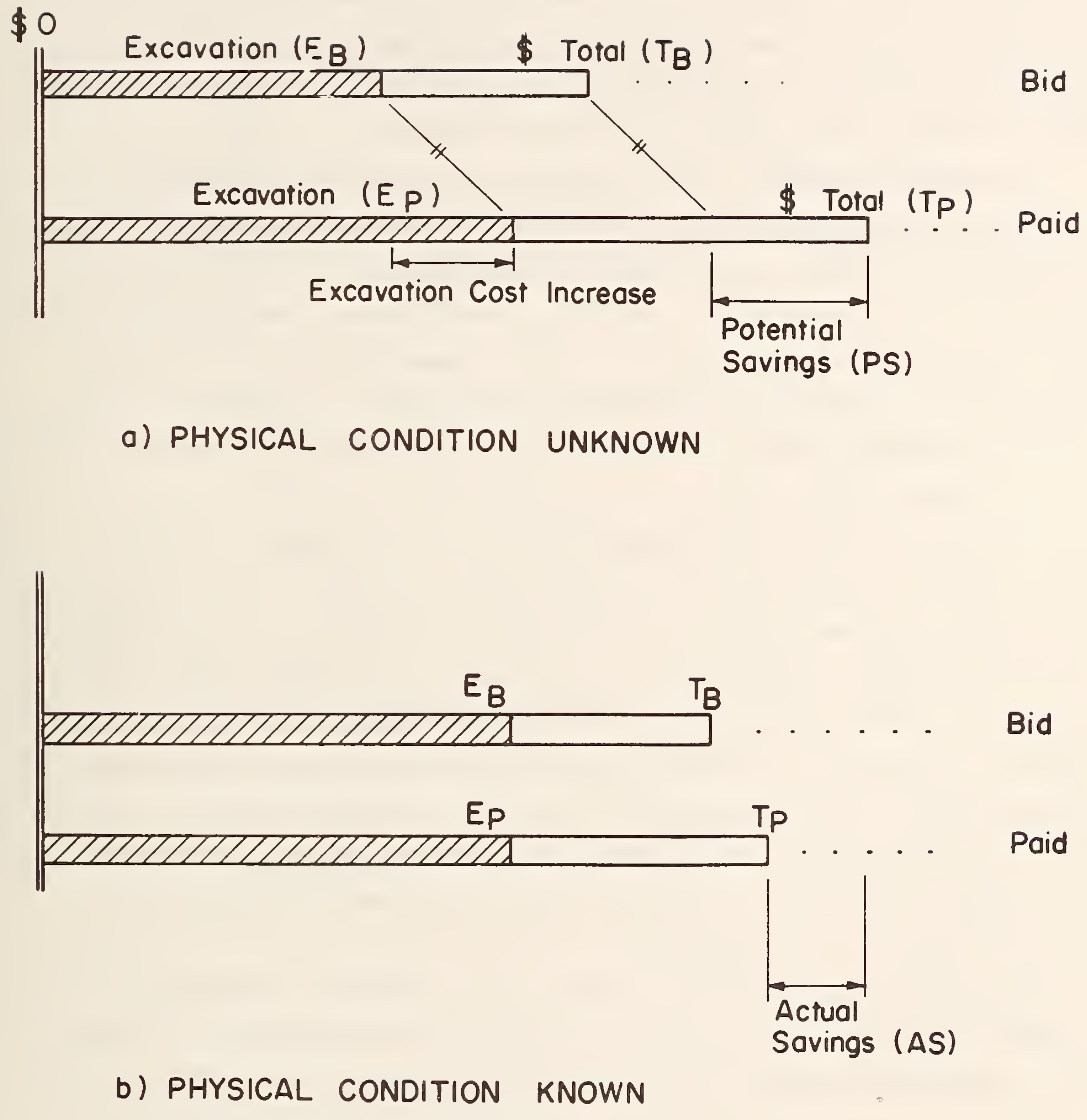


FIGURE 4.4 DIFFERENCES BETWEEN EXCAVATION COSTS AND PROJECT SAVINGS

VERTICAL BORINGS AND TESTING COSTS

This section presents methods of estimating costs of tunnel exploration with vertical borings for various regions of the U.S. The exploration model was partially based on the soft ground sections of the exploration program conducted for the Washington Metropolitan Area Rapid Transit (WMATA) system (Mueser, Rutledge, et al, 1967).

The number, length, type of borings and samples from each section and phase of exploration were summarized, as shown in Tables M.1 and M.2 of Appendix M. Each cost parameter was expressed in terms of a parameter related to exploration or to the tunnel itself--e.g., undisturbed samples per boring; observation wells per foot or tunnel (reciprocal of well spacing), etc. When there were variations within the parameter itself, as with different diameter borings and samples, weighted averages provided a representative cost.

The average depth of boring (wash boring plus rock core) in the WMATA case was estimated to be 55 ft (17 m). Therefore, the number of laboratory tests and samples recovered (as described in the exploration report for WMATA) applied only to borings of that average depth. Correction factors of 1.25 and 1.4 were then applied to increase the sampling and testing quantities to those likely with borings 100 and 500 ft (30 and 150 m) deep respectively. These factors are arbitrary. However, they are based on the assumption that only changes in stratum and soil properties in the general tunnel area need be defined rather than over the total boring depth.

The cost of an exploration program is a function of geologic and economic variables, both of which are dependent on geographic location. Therefore, data was collected for two regions and averaged when possible to account for regional variations. Haley and Aldrich Consulting Engineers (Cambridge, Mass.) were the primary source of drilling data for the Northeast. Their data are based on a collection of bids received from boring contractors for projects on which they were consultants. Testing costs were furnished by Haley and Aldrich and Woodward-Moorhouse (Clifton, N. J.). From the South, prices from one consulting firm for boring and testing were used (Louis J. Capozolli & Assoc., Baton Rouge, La).

The cost of drilling, sampling and testing per boring for three exploration depths and environments was determined. Drilling costs include: (1) "average" dry land exploration, (2) within a Central Business District, and (3) over water. In addition, the cost of cone penetrometer probes (from Ardaman & Associates, Ft. Walton Beach, Fla.) between borings (to locate obstacles and serve as a property index) was determined. The sum of these costs was normalized to three boring spacings and is expressed in Figure 4.5 as "total" exploration cost in dollars per cubic foot of tunnel ($/CF). This cost was converted from dollars per linear foot as indicated on the figure.

The conversion to dollars per cubic foot of tunnel was made so that a valid comparison could be made between vertical and horizontal exploration. It is within this context that the concept of effective explored volume arises. Presumably, a horizontal hole would be within the proposed tunnel and therefore would have a 100% effectiveness. However, only a fraction of a vertical borehole falls within the tunnel limits and therefore is less than 100% effective. It was assumed that the last two tunnel diameters of a vertical hole represented the effective explored volume. Two tunnel diameters are approximately 50 ft (15 m), the base depth. At greater depths (100 and 500 ft), the costs of testing were multiplied by 1.25 and 1.4, respectively, to account for a sampling and testing above two tunnel diameters to detect changes in strata.

The exploration costs presented in Figure 4.5 represent a lower bound to the true exploration costs for an average tunnel project. Special field tests, which were connected for the Washington project and which are a necessary supplement to sampling and testing, were not included. The special tests included: test pits, pump tests, water pressure tests, borehole photography, and seismic surveys. Costs of collecting and evaluating and presenting the data are not included. The cost of an earlier investigation, and collection of previous boring logs is not included.

Every exploration program, whether horizontal or vertical, would have a preliminary investigation (as mentioned in the discussion of scope, Section 1.6) and would incur collection, evaluation, and

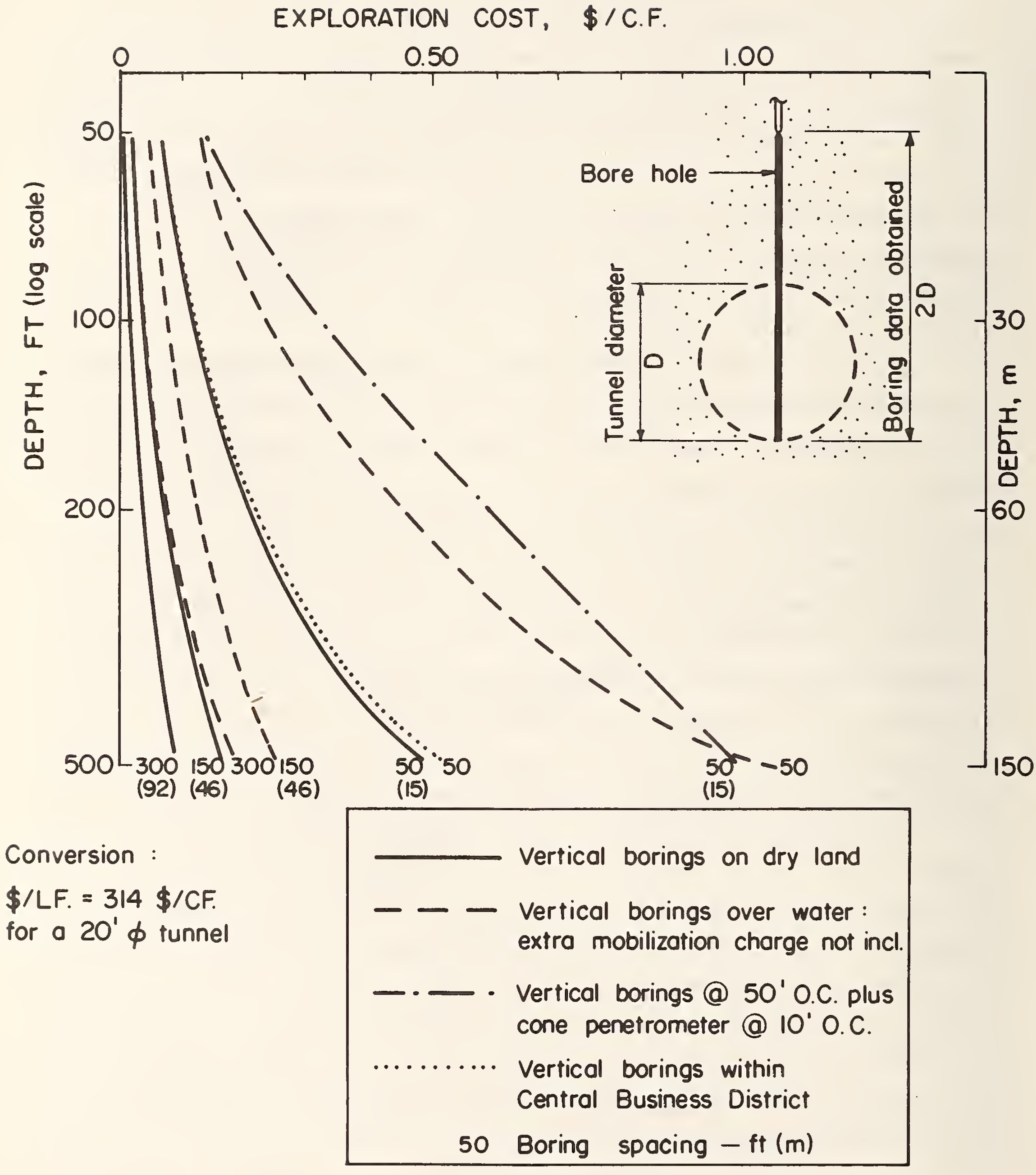


FIGURE 4.5 EXPLORATION COST : VERTICAL BORING CONFIGURATION

presentation costs. Therefore these costs should not be included when comparing the two methodologies.

ACCURACY AND CONSIDERATIONS OF VERTICAL BORING

The accuracy with which stratification, bedrock depth, soil properties, etc., are established will greatly affect the assessment of risk for design and construction, and therefore project cost. In any type exploration program, since an infinite sample is required to determine the exact state of nature, the objective is to sample a representative portion of the tunnel alignment, or those areas in which the uncertainty is highest. A vertical boring is an inexpensive method of determining the soil conditions <u>at a point</u> for shallow tunnels. However, such a small percentage of the total tunnel volume is sampled, that sampled conditions must be linearly interpolated or extrapolated to approximate the conditions at any point not on the sampled vertical line.

Two types of limitations may reduce the value of vertical borings as an exploration technique--uncertainty of the state of nature between borings and faults within the technique. The first is an interpretation technique wherein troublesome conditions may not be detected. These conditions may be rock pinnacles, correct boulder size and frequency, and small lenses or running ground. The second limitation involves the difficulty of obtaining reliable physical parameters with present boring techniques. Lack of precise correlations between index tests and properties and sample disturbance often lead to conservative and therefore costly design.

SURFACE GEOPHYSICAL EXPLORATION COSTS

The cost per foot of the surface geophysics methods are shown in Table 4.2. These costs assume a 1 to 2 mile (1.6 to 3.2 km) tunnel length and that some cross-profiles would be investigated in addition to center-line study. A typical tunnel investigation will most likely require a minimum of three times the tunnel length in actual profile coverage and may require as much as ten times the length in coverage for a very detailed investigation. Obviously, the greater the coverage,

the less the risk of encountering unanticipated conditions in the actual tunnel construction.

TABLE 4.2: COSTS OF SURFACE GEOPHYSICAL METHODS
$/ft ($/m)

Method	On Land	Underwater
Seismic Refraction	.75 - 1.50 (2.5 - 5.0)	1.00 - 2.00 (3.3 - 6.6)
Seismic Reflection	1.00 - 3.00 (3.3 - 9.9)	.75 - 1.25 (2.5 - 4.0)
Vertical Hole Refraction*	27 (88)	
Electrical Resistivity	.50 - .75 (1.6 - 2.5)	1.00 - ? (3.3 - ?)
Electromagnetic Profiling	2.00 (6.6)	

* Based upon 100 ft (30 m) deep tunnel with holes spaced at 100 ft (30 m). See Table M.17 in Appendix M. This is not seismic cross hole.

REFRACTION SURVEY CONSIDERATIONS

A norm for predicting refraction survey accuracy is a variation of ±10% from actual; that is, a depth reported from a seismic survey line should agree within 90 to 110% of the depth disclosed during excavation. This accuracy will hold in areas where subsurface interfaces are nearly planar, velocity contrasts between layers are approximately 1.25 to 1.5+, and crosslines are also investigated.

Two situations are particularly responsible for larger variations. First, a "blind zone" of an intermediate velocity layer over rock (dense TILL, or weathered ROCK) cannot be seen. Secondly, a shallow high velocity layer (e.g., thin cemented layer) can mask refractions from the deeper rock. Detection of these conditions require borings. Therefore, small "blind zones" are almost undetectable. Further discussion of these situations can be found in Appendix M.

At this point, the primary geophysical advantage of horizontal holes close to grade becomes evident. Sensing from horizontal holes close to grade eliminates shallow high velocity zones, decreases the absolute error because of shorter wave travel, and can eliminate the blind zone error. It is these advantages which make horizontal boring geophysically advantageous, even if only refraction surveys are conducted.

REFLECTION SURVEY CONSIDERATIONS

Because of the high resolution nature of this method, accuracy of interface profiling is usually in the order of a few percent of actual, if accurate velocity information is available (either by assumption or based on refraction measurements). The depth errors based on incorrectly assumed velocity values are directly proportional to the percentage difference from the assumed value of 5,000 ft/sec (1,524 m/sec).

As with electromagnetic surveys, the main limitation for high resolution surveys will be penetration. The maximum penetration depth is a function of energy coupling and frequency. See Appendices J and M.

ELECTROMAGNETIC SURVEY CONSIDERATIONS

The electromagnetic survey system considered is a downward-looking radar system from Geophysical Surveys, Inc. It can be used to locate subsurface utilities and obstructions. Costs per foot are shown in Table 4.2.

On one job, utilities were located to a depth of 10 ft (3 m). However, sewer lines were not detected, probably due to the depth of the sewer lines. In another job, the radar unit was able to locate and record elevations of pipelines in the Mississippi River. In fresh water operations, limits of penetration are about 18 to 20 ft (6 m). Penetrations of up to 50 ft (15 m) have been possible only in <u>dry sand</u>. However, penetration in saturated clay is limited to 2 to 5 ft (.6 to 1.5 m). Because of the high frequencies, penetration rather than resolution is the chief limitation.

VERTICAL BOREHOLE GEOPHYSICS: COSTS AND CONSIDERATIONS

The cost per foot of the borehole geophysical methods are shown in Table 4.2. See Table M.17 in Appendix M for details. Note that in many cases the boreholes might already exist from preliminary survey work, and thus the additional cost for the geophysics work is variable depending upon borehole spacing.

Geophysical exploration from within a soil mass is subject to the same general considerations mentioned previously for surface geophysical exploration. However, there are several advantages over surface geophysical techniques.

The same accuracy of ± 10 % can be expected. But because of the decreased depth of penetration to the surface being profiled, the depth uncertainty is reduced. In addition, penetration decreases the averaging effect encountered in heterogeneous soil masses.

A very important advantage of downhole geophysical exploration is the potential for eliminating the blind zone discussed under refraction surveying. The blind zone is eliminated by placing the source and receiver nearer to, or within, the blind zone. The comparison of the surface and downhole refraction accuracies is shown in Figure M.1 in Appendix M. The horizontal system could be replaced by a series of vertical holes.

Cross hole techniques have also been discussed in another FHWA report, "Improved Subsurface Investigation for Highway Tunnel Design and Construction," FHWA-RD-74-30, Vol. 2 (Rubin et al., 1974).

4.4 COSTS OF HORIZONTAL PENETRATION AND EXPLORATION METHODS

The alternative horizontal exploration methods investigated were as follows:

- --Mandrel excavating system with and without continuous navigation, with and without improved mud techniques, and with and without a follower geophysics package.
- --Thrust applicator excavating system with continuous navigation, with and without on-board sensing, with and without a follower geophysics package, and with and without an on-board geophysics package.

Description of the excavation and navigation equipment is contained in Chapter 2, while the exploration equipment is described in Chapter 3.

MANDREL PENETRATION COSTS

Figure 4.6 presents penetration costs for the Mandrel system based on Titan Contractors' bid estimates for drilling their pilot holes. These costs are based on single contractors WHO ARE BORING ALL YEAR. If they cannot bore all year, costs will go up significantly. Details concerning the origin of this plot are presented in Appendix O. Market conditions assume a single active firm with variable length, single contracts. Maximum penetration distances per set-up are 1500 ft (460 m) for their current approach (labeled OLD) and 3000 ft (920 m) with improved mud techniques and continuous navigation (labeled NEW). The difference between BID and OPT on the graph accounts for problems resulting from collapse of hole and subsequent loss of lubricity. BID assumes occasional loss of lubricity and unforeseen problems. The NEW configuration includes a continuous navigation package; the OLD configuration has a stop and survey package.

It can be seen that the average job must be greater than 4000 to 5000 ft (1200 - 1500 m) (minimum of 2 penetrations) to justify the NEW configuration. This non-benefit of increased technology results partially from unproductive cost of highly skilled technical personnel during mobilization and demobilization.

THRUSTER PENETRATION COSTS

Figure 4.7 shows penetration costs for the thruster system based on basic equipment costs for CONOCO's system. Market conditions are the same as for the Mandrel. Four configurations are shown in this curve--two assuming a drill rate of 5 ft/min (1.5 m/min) and two assuming a drill rate of 2 ft/min (0.6 m/min). Each of these sets is further divided into move and no-move. No-move means the entire length of the job is penetrated with one placement of equipment (i.e., the maximum

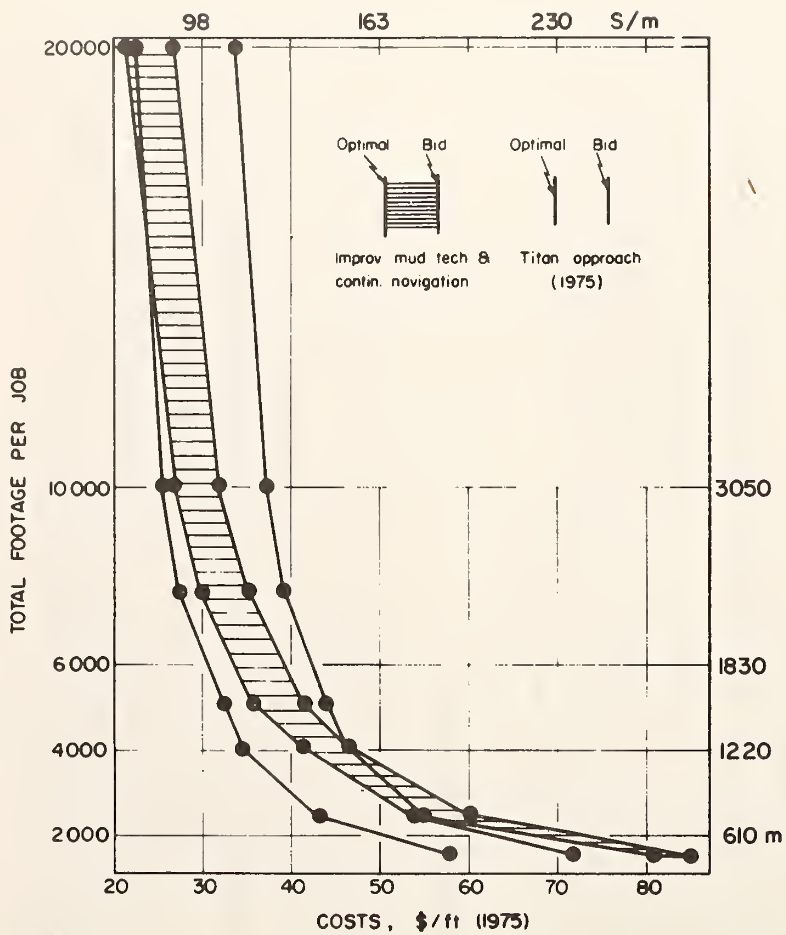


FIGURE 4.6 MANDREL PENETRATION COSTS

INCL.

DRILLING CONDITIONS, TECHNOLOGY IMPROVEMENT & MARKET CONDITIONS

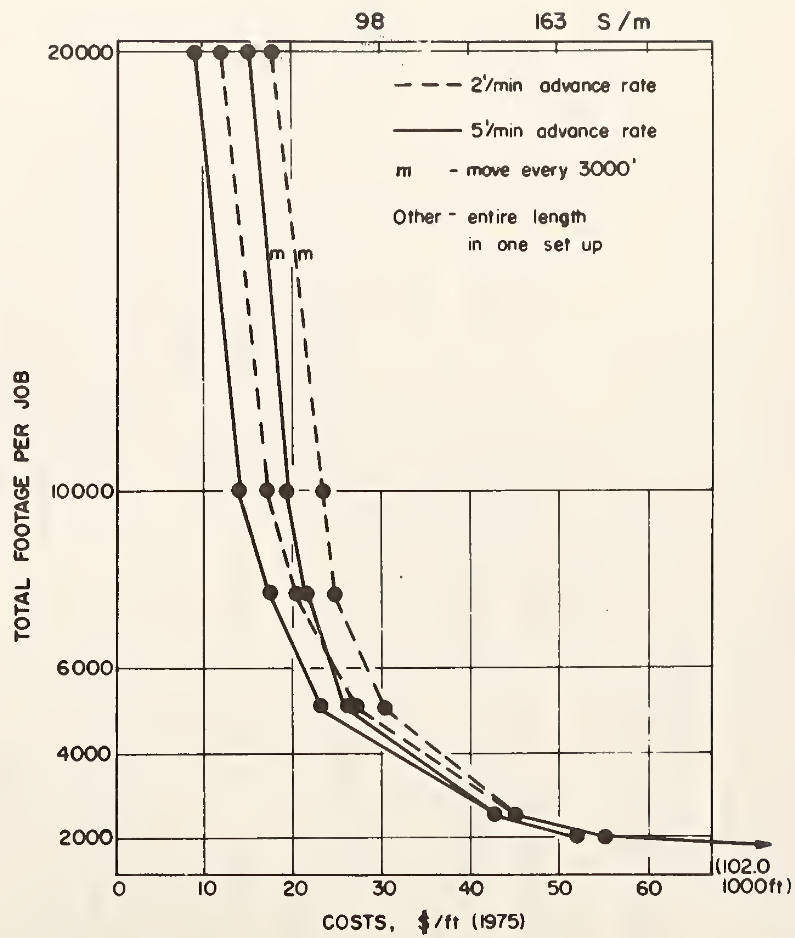


FIGURE 4.7 THRUSTER PENETRATION COSTS

INCL.

DRILLING CONDITIONS, TECHNOLOGY IMPROVEMENT & MARKET CONDITIONS

penetration of the equipment is 20,000 ft/6100 m). The move means that the equipment is reset every 3000 ft (915 m), i.e., the maximum penetration is 3000 ft (915 m).

THRUSTER-MANDREL COMPARISON

The 2 ft/min-move configuration for the Thruster system is the configuration which is most comparable to the Mandrel system. It can be seen that cost per foot of the Thruster is less than cost per foot of the Mandrel. However, in jobs to date the Thruster has penetrated only 800 ft (244 m) while the Mandrel has penetrated 1700 ft (518 m). The Mandrel system requires an investment of $150,000 to $300,000 to purchase equipment and build horizontal drilling rig, etc., while the Thruster requires $50,000 to $100,000 to purchase equipment. However, development and test investments must be made for both systems--more for the Thruster than for the Mandrel--to increase total penetration distances. Development and testing are also required for both to build and test interfacing hardware for the purchased exploration components and to test the entire system in an on-site environment. Costs for interfacing and testing would most likely be in the range of 1 to 2 years with 12 engineers.

NAVIGATION AND BIT COMMUNICATION COSTS

The proposed navigation/survey package is described in Chapter 2 and Appendix E. The cost of producing a working prototype of gyro (2) — accelerometer (3) system is estimated to be in the order of $100,000. It would take a minimum of 1 man-year to design the housing and electronics to accompany the onshelf gyros and accelerometers. This cost is independent of the communication system.

Several firms have magnetometer (3) — accelerometer (2) systems; Telcom, CONOCO, and the Draper Lab. Only the Telcom system could be available commercially for a Mandrel penetration system. CONOCO might be willing to market its system for Thruster systems.

Proposed bit communication systems were also discussed in Chapter 2 and Appendix E. For the Thruster system, bit communication offers no problem, since a continuous cable is already an integral part of the

system. The Mandrel, on the other hand, must communicate via the drill steel. Further development of the present system (Telcom) funded by the U. S. Bureau of Mines will require at least $100,000.

The development costs of these systems will increase the operational costs of the excavation systems by only $2 to $3 per foot ($6 to $10/m). See Appendix P for a detailed explanation.

ON-BOARD AND FOLLOWER SENSING TRADEOFFS

The prime factor affecting the comparison of on-board sensing versus follower sensing is one of time. As shown in Table 4.3, some measurements require stops of 10 minutes to 2 hours. For geophysical measurements, even though stops would be short, it is doubtful whether the sensing equipment would be able to function optimally in the environment of the excavating system due to vibrations. See Appendix J. for further discussion. During excavation, it would be highly undesirable to stop since even with the best of mud techniques, loss of lubricity would be likely due to settlement of fines. Jamming due to settlement and hole collapse have been found to be major problems affecting Titan's operation. Normal force required for advance increases substantially upon cessation of pumping.

Because of the high risk involved with stopping, it is recommended that parameter sensing be performed with a follower package and that this package be pulled through the hole after the excavating system exits.

The only sensing equipment which should be further investigated for on-board use is the piezometer cone and seismic sensing. Coupling seismic equipment to the bit presents the engineering problem of connecting a stationary lead to a rotating instrument. It is recommended that this system be attempted only with the Thruster because of the great difficulty of stringing continuous cable through discontinuous drill steel. See Chapter 1 and Appendix E for further details. Development of on-board sensing would most likely involve a one-year effort with six or more engineers. (See Chapter 3 for instrumentation details.)

FOLLOWER PACKAGE COSTS

One method for sampling geo-hydrological properties of the proposed alignment is to place the geophysical equipment in a separate package

TABLE 4.3: STOPPING TIME FOR DOWNHOLE SENSING

PARAMETER	METHOD	MEASUREMENT TIME
Penetration Rate Torque Normal Force Fines Inspec. Permeability Penetration Resist. Soil Type	direct pump pressure load cell direct inductance cone piezometer	NO STOPPING
Modulii (Dyn.) Seismic Velocities	seismic	1 - 2 minutes
Permeability (Sand) Cone Adhesion Static Pore Pressure (Sand) Relative Density	cone piezometer	10 minutes
Permeability (Clay) Static Pore Pressure (Clay) Lateral Stress Strength Modulii (Static)	cone piezometer hydraulic fract. pressuremeter	60 to 120 minutes
Samples	side wall	follower only

which would be towed by the excavating system or pulled through after the excavating system exited. Exact development and operational costs for this package cannot be determined since it should be designed (i.e., the specific geophysical equipment chosen) for the particular site from preliminary information. However, costs can be approximated from a time-motion case study of a directional reflection survey in five 130 ft (40 m) vertical holes. It is assumed that other follower packages will involve similar costs.

Analysis of actual charges and work efficiencies allowed the following assumptions for calculating operating costs:

Equipment warm-up and adjustment 1.5 hrs/day

Transmissability test is necessary every 100 ft (300 m). Will take one day

Sensing speed in case study was 0.5 ft/min (.15 m/min) for sensing at 4 orientations. This speed includes automatic recording of data

Assumed sensing speed will be 2 ft/min to account for advances, such as multiple position sensing

Labor force includes 2 technicians and 1 supervisor

Report costs and probe insurance cover computerized data reduction and equipment depreciation.

Table 4.4 presents the per foot incremental costs (as derived from the reflection survey case study) of geophysical sensing when combined with horizontal penetration. On-board geophysical sensing results in slower penetration rates of 2 ft/min (0.6 m/min) and could slow penetration down to as little as 0.5 ft/min (.15 m/min). These advance rates are averages and include stopping at each station for as much as 1 minute. If there is no improvement in advance rate over the present 0.5 ft/min (.15 m/min), then the costs will increase from the \$7.50/ft (\$24/m) level to the \$8.50/ft (\$28/m) level and simultaneous penetration and sensing will be impossible.

TABLE 4.4: COSTS OF IN-HOLE HIGH FREQUENCY REFLECTION SURVEY

Cost Item	Distance Investigated--ft (m) 2,500 (762)	5,000 (1,525)
Travel	1,100	1,000
Velocity Measurement	6,000	6,000
Reflection	9,545	26,250
Reports	250	250
Insurance	100	100
Probe Insurance	850	1,530
Supervisor	1,500	2,500
	19,345	37,730
Total Per Foot	7.74	7.55

4.5 VALUE OF ALTERNATE EXPLORATION METHODS

A scenario approach was adopted to determining the "best" method for exploration of a given geology. Simplification to scenarios was necessary for two main reasons: First, only hypothetical probabilities of occurrence of a condition are available for a non-site-specific study. Secondly, as discussed in Appendix J concerning geophysical exploration, a comparative assessment of the reliability of different exploration methods does not exist because of the interpretational nature of geophysical exploration.

Thus, for the scenarios it was assumed that given unanticipated conditions did exist (probability = 1) and that the reliability of the exploration methods could be subjectively assessed.

There are scenarios for two principal unanticipated conditions: running ground and boulder obstruction. These scenarios are presented in detail in Appendix P. Each scenario includes a marginal tunneling cost estimate of an unanticipated condition (MV) which is a function of exploration approach. The marginal costs, discussed in Section 4.3, are

the "values" of subsurface exploration as they could be eliminated by extensive investigation. Each scenario will also include marginal exploration cost estimates, MC. These marginal costs are separated into two groups, exploration from the surface--discussed in Section 4.4, and horizontal exploration--discussed in Section 4.5. Ratios of MV/MC for each scenario are compared for alternative exploration methods and two tunnel invert depths, 75 ft (23 m) and 150 ft (46 m). By comparing these ratios, the "best" method for exploring a specific unanticipated condition--scenario--can be found as a function of the tunnel depth.

The following modes of exploration are compared:

(1) Vertical Borings at the following intervals:
   (a) 300 ft (91 m)
   (b) 100 ft (30 m)
   (c) 50 ft (15 m)
(2) Vertical Boring at 50 ft (15 m) intervals plus cone penetrations at 10 ft (3 m) intervals
(3) Surface Refraction Studies (reflection with sufficient resolution is impossible)
(4) Horizontal Boring and On-Board Geophysical Sensing (Thruster only)
(5) Horizontal Boring and a Following Geophysical Package

The main conclusions from the boulder and running sand scenarios are as follows:

> Any exploration for boulders with borings spaced less than 300 ft (92 m) is highly beneficial--PROVIDED THE BOULDERS ARE EQUALLY LIKELY ALONG THE EXPLORED SECTION.

> Any extended exploration for running sand beyond vertical borings (reflection/refraction geophysics is of little value to determine whether soil will or will not run) is MORE beneficial than that for boulders--PROVIDED THE RUNNING SAND LENSES ARE EQUALLY LIKELY ALONG THE EXPLORED SECTION.

Horizontal boring becomes the most cost effective method of exploration at depths greater than 75 to 100 ft (23 to 30 m). For shallow depths intensive vertical boring is still the cheapest alternative--PROVIDED ACCESS IS AVAILABLE AND THE AREA IS NOT ENVIRONMENTALLY SENSITIVE.

Exploration by Mandrel is only slightly more expensive than exploration by Thruster. The costs in the analysis were operational only. Therefore, since the Mandrel system can penetrate further (at this time) and involves less developmental expenditure than the thruster system, it is the lower cost alternative--PROVIDED GEOPHYSICAL AND CONTACT SENSING IS PERFORMED WITH A FOLLOWER.

The operation of the follower sensing system is cheaper than the on-board sensing system. It is cheaper for two reasons: (1) less development cost is necessary because of no interfacing and (2) the follower system can be operated after excavation is completed and no standby expenses are incurred.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The major conclusions are summarized in Chapter 1. This chapter presents detailed conclusions and recommended options for future action. The conclusions and recommendations will be organized by appendix (D through P). Each recommendation is ranked as follows: low (L), medium (M), high (H), and very high (VH).

5.2 EXCAVATION EQUIPMENT

MOTORS

Conclusion: The hydraulic motor is the most efficient for small holes and allows use of the forward module space. Electric motors MIGHT allow excavation without total removal of cuttings.

Recommendation: The hydraulic motor should be tested in situ. Estimated cost is $50,000 (RANK = M). Consideration should be given to excavation with only partial removal of cuttings to avoid hydraulic fracture (RANK = L).

THRUST APPLICATORS

Conclusion: The DRILCO device is the only presently operable and field tested (in soft coal and caliche soils) device. The larger model (8 in./20.3 cm hole diameter) could be adaptable to soft soil. The mechanical pad contact pressures will have to be adjustable.

Recommendation: The DRILCO device should be modified for larger pads and selectable pad pressures. Estimated cost is $50,000 to $100,000 (RANK = H).

DIRECTION CONTROLLERS

Conclusion: The deflection shoe concept is adequate for soft coal, clay-shale, and possibly dense, silty sand. A universally orientable articulated sub, similar to the Dyna-Flex, may be necessary in soft clay to facilitate continuous excavation.

Recommendation: Improve upon Dyna-Flex concept to eliminate plunger, make compatible with continuous navigation, and move bend closer to the bit. Estimated cost is \$50,000 to \$100,000 (RANK = VH).

SOFT GROUND BITS

Conclusion: No present bit can handle both clayey silt and core-stones of residual soil.

Recommendation: Residual soil bits need to be developed. Possibly special roller cones with diamond inserts and controllable jetting ports. Estimated cost is a maximum of \$100,000 (RANK = M).

5.3 NAVIGATION EQUIPMENT

NAVIGATION/SURVEY

Conclusions: Magnetic navigation equipment is totally inappropriate in urban environments; continuous navigation systems are necessary to decrease operational costs (by 2) but are dependent upon miniaturization and continuous communication.

Recommendation: The concept in Appendix E for a small, updatable gyro system should be developed. The estimated cost is \$100,000 (RANK = VH).

COMMUNICATION

Conclusion: Private investment for 12 in. (30 cm) diameter rotary equipment is intense in this field ($\approx \$4 \times 10^6$); therefore, government investment should consider possible spinoff.

Recommendation: The least investment alternative would be

perfection of a drill steel communication system for the mandrel. Estimated cost is $100,000 to $200,000 (RANK = VH). The alternative is perfection of thruster excavation to utilize the cable for communication. The estimated cost is the sum of developing the thrust applicator, and the hydraulic motor, an adaptable bit and field test is ≈ $525,000 (RANK = M-H).

5.4 DRILLING FLUID

TRANSPORT OF CUTTINGS

Conclusions: There is little published data for bentonite slurry transport of materials in horizontal pipes. Oil drilling approaches involve fan viscometer tests to approximate energy consumption. Preliminary viscometer experiments indicate that head losses will increase because of cuttings which increases the danger of hydraulic fracture.

Recommendations: Basic experiments should be conducted to measure annular flow head losses resulting from cuttings transport. Estimated cost is $30,000 (RANK = M-H).

HYDRAULIC FRACTURE

Conclusions: Hydraulic fracture has been observed in silty sands at depths greater than 100 ft (30 m). Therefore shallow exploration in sand is not recommended.

Recommendations: Basic experiments should be conducted with a hydraulic fracturing system to confirm analysis. Expected cost is $30,000 (RANK = L-M).

CABLE/PIPE FRICTION

Conclusions: The smallest cable or pipe friction will result if cable is constructed to be neutrally buoyant or pipe has internal return. Maximum penetration will be limited principally by keying of cable or pipe at sharp bends.

Recommendations: Neutrally buoyant cable should be pulled through pre-excavated holes to measure friction. Estimated cost would be small, $5,000, if combined with other in situ tests (RANK = L). Also miniaturization of internal return systems should be investigated (RANK = M).

FILTER CAKE EROSION

Conclusions: Experimental erosion tests seem to have been conducted with turbulently flowing, clean water. Even with this inapplicable data (slurry will be laminarly flowing at the same velocity), the holes appear to be erosively stable.

Recommendations: Perform basic measurements of erosion susceptibility with laminarly flowing, bentonitic slurries. Estimated cost is $30,000 (RANK = L-M). In addition, single grain stability investigations need vertification (RANK = L-M).

5.5 SOIL MACHINE INTERACTION

MANEUVERABILITY

Conclusions: Thruster systems can tolerate 9 to 15^{o}/100 ft (9 to 15^{o}/30 m) build angles for sustained penetration. Mandrel systems can tolerate 5 to 9^{o}/100 ft (5 to 9^{o}/30 m) build angles for sustained penetration. Detailed field information is fragmentary. Maximum build angle is limited by internal (component) stiffness in soft soils. Therefore shorter components are critical to larger build angles.

Recommendations: CONOCO has more detailed information on drill paths and build angles. Even though this information is proprietary, it would be helpful to obtain such information. Mandrel data are fragmentary. Therefore, field tests with constant measurement are necessary (RANK = L).

MAXIMUM PENETRATION

Conclusions: As of 1975, the mandrel system had penetrated 1700 ft (515 m) with washover pipe. The thruster system had

penetrated 800 ft (240 m). These systems both have potentials for reaching 2000 to 3000 ft (600 to 900 m) penetration. The thruster system will be limited by bit wear. Both systems will be susceptible to hydraulic fracturing at shallow depths.

Recommendations: See MOTORS, Section 5.2, and CABLE/PIPE FRICTION Section 5.4.

5.6 HOLE STABILITY

STATIC STABILITY

Conclusions: Theoretical calculations and laboratory tests indicate static stability of horizontal, mud-filled boreholes is possible in most soils--except permeable gravels and very soft clays. The composition of the mud is critical to stability. Hydraulic fracture can occur but does not necessarily result in hole collapse.

Recommendations: See HYDRAULIC FRACTURE and FILTER CAKE EROSION in Section 5.4.

DYNAMIC STABILITY

See FILTER CAKE EROSION in Section 5.4.

5.7 DISTURBANCE AROUND HORIZONTAL HOLES

STRESS REDISTRIBUTION

Conclusions: Soil disturbance is larger around horizontal holes than around vertical holes. Therefore indices and empirical relationships derived from partially disturbed vertical samples may not be applicable to horizontal samples.

Recommendations: Solutions for extent of plastic zone for conditions of $K_o \neq 1$ are possible by computer. Publication of dimensionless results of these studies would aid tunnel design. The usefulness of these results is not of immediate value to this study.

CONTACT DISTURBANCE

Conclusions: Disturbance from extension of anchor pads and deflection shoes of the thruster system, and bearing of the wash-over pipe will extend from 1/2 to 1 diameter outward from the hole.

Recommendations: Because of the contact disturbance, and the stress redistribution, development of testing equipment for undisturbed testing of soil properties along the borehole wall will be of little value. Therefore equipment should be developed which can be positioned in the forward module (See Figure 2.1) and/or extended one hole diameter into the soil. See Section 5.9 for costs and rank.

5.8 GEOPHYSICAL EXPLORATION AND SUBSURFACE GEOMETRY

FORWARD SENSING

Conclusions: Forward sensing cannot be accomplished in holes smaller than 7 to 8 in. (17.5 to 20 cm) in diameter, and orientation of reflected objects will be difficult to predict. In addition, expected minimum detection distances are small compared to distances necessary for avoidance without backing up.

Recommendations: Since horizontal boring is usually uneconomical for exploration above depths of 75 to 100 ft (23-30m) and most man-made objects are above 100 ft (30 m), it will be necessary to see these objects only at entrance and exit sites when horizontal boring is employed. Surface methods are best employed at these locations. Therefore, forward geophysical sensing should only be pursued in the final stages of development.

ALL AROUND SENSING

Conclusions: Published attenuation data for seismic waves in soft ground (saturated soil) indicate high loss of energy which increases linearly with frequency and distance. Seismic refraction/reflection surveys from horizontal boreholes below the ground-water table and horizons of variable velocity will yield high

quality information about the bedrock surface. The sparker seismic energy source appears to have a more compressed signal than the air gun. Both air guns and sparkers can fit in the forward module. Size resolution is proportional to separation distance such that a 10 ft (3 m) boulder can be detected no further away than 30 ft (9 m). No object can be seismically detected closer than 6 ft (2 m) because of bubble implosion. Angular resolution without further development will not be better than ±20 to 25°.

Recommendations: A small piezoelectric source is needed for detection of objects within the bubble window. A field demonstration with existing seismic equipment pulled through a pre-excavated hole should be conducted to check overall feasibility before further sophisticated equipment (filtering systems or combination with excavation systems) is promoted. Estimated cost is $15,000 to $30,000 for geophysical tests only (RANK = VH--if horizontal hole is available).

5.9 SOIL AND WATER PARAMETERS

Conclusions: Valuable information can be obtained from the excavation process alone. Non-intersection of rock decreases probability of erratic boulders or rock pinnacles. All contact sensing (with the exception of the cone piezometer and instrumentation of anchor pads) will require stopping which will lead to jamming of cable or mandrel. Even reflection surveys may require stopping to decrease background noise.

Recommendations: The cone piezometer should be developed. It can be employed to measure penetration resistance and density/soil type with constant penetration. It can also measure permeability and static pore pressure if advance is stopped. The latter measurements are perhaps best performed with vertical borings because of required stopping. Estimated cost for development independent of forward space module is $35,000 (RANK = VH); within forward module is $100,000 (RANK = L--until excavation perfected).

Electromagnetic nuclear response logging may provide a means of determining permeability with a follower package. Laboratory experiments should be conducted to validate the usefulness of this tool. Estimated cost is $30,000 (RANK = L--until excavation perfected).

Caliper techniques should be developed for monitoring the collapse of a pre-excavated hole when mud pressure is lowered. In this manner valuable information concerning the stand-up behavior of a subsequent tunnel can be obtained. Estimated cost for DEVELOPMENT AND TESTING (not including hole costs) is $50,000 (RANK = H--because it is a consideration in excavation).

5.10 COSTS OF UNANTICIPATED TUNNELING CONDITIONS

Conclusions: Case history data indicate that the costs can range from $500/ft ($1,640/m) for unanticipated boulders to $1,300 to $2,000/ft ($4,300 to $6,600/m) for unanticipated running ground. These costs are only for the sections of tunnel with the unanticipated condition.

Recommendations: Because costs are only for those sections with problems, more research should be conducted to comparatively find probabilities of adverse conditions as a function of geology and intensity of exploration. Expected cost of such a study would range from a minimum of $20,000 to $70,000 (RANK = M). Advertizement of the cost conclusions is necessary (RANK = VH).

5.11 COSTS AND LIMITATIONS OF SURFACE EXPLORATION

Conclusions: Chapter 4 contains comparative costs and limiting features of vertical boring and cone penetration and surficial geophysical exploration methods. The details are too numerous to list here.

Recommendations: Geophysical exploration is inexpensive on a per foot basis which suggests it should be employed more. However, its interpretational nature and required correlation and check borings suggest caution in its use. Cone penetrometer probes are

useful indicators of the regularity of corestones or rock surface and should be employed more in exploration for shallow tunnels.

5.12 CERRITOS CHANNEL: DETAILED OPERATIONAL STUDY

Conclusions: The information contained in this chapter is detailed enough to enable the chapter to serve as an operations manual. No lengthy environmental impact statement was required, provided the entrance and exit elevations were above the channel level.

Recommendations: The Department of Transportation--specifically its pipeline transport group--should sponsor further implementation and development of the horizontal boring method of pipeline placement beneath rivers and roadways. This method is both monetarily and environmentally advantageous; it can save up to 1 year and $100,000 in environmental impact statement preparation per crossing (RANK = VH).

5.13 OPERATIONAL COSTS OF EXCAVATING SYSTEMS

Conclusions: The operational costs of the thruster and mandrel systems are similar and will be a function of the number and type of contracts available each year. The costs are heavily influenced by mobilization and demobilization expenses. For example, if 2000 ft (600 m) contracts at separate locations are available, the cost per foot of boring will be approximately $62/ft ($205/m) for mandrel and $55/ft ($182/m) for thruster. If 4000 ft (1200 m) contracts are available (even if two set-ups are required), the costs should decrease to $46/ft ($152/m) and $37/ft ($111/m) respectively.

Recommendations: The mandrel system with washover pipe is the most adaptable system with least development costs to test exploration concepts. The thruster system has the most potential in terms of both maneuverability and maximum penetration, but has higher development costs.

To decrease costs for the mandrel system, a continuous navigation/communication system and a universally flexing bent sub or housing (similar to a Dyna-Flex) should be developed. To decrease costs for the thruster system--in soft clays--a universally flexing bent sub or housing and downhole valving allowing variable contact pressure should be developed. The present thruster system is adequate for stiff to very stiff clays. See Section 5.2 and 5.3 for estimated costs and ranking of recommendations.

5.14 SCENARIOS FOR VALUE ANALYSIS

Conclusions: Operational costs are high enough that even if there was no potential for hydraulic fracture, tunnels shallower than 100 ft (30 m) are best explored with vertical techniques. Horizontal boring is cost effective only for deeper tunnels or where vertical access is difficult or prohibited by environmental concern.

Continuous excavation with subsequent geophysical and contact sensing will involve lower costs than on-board sensing. The costs will be lower because of decreased technical difficulties and less interference and interaction of personnel involved in exploration and sensing.

Recommendations: First generation excavation systems exist and it appears uneconomical to measure soil properties while excavating. Therefore, existing exploration equipment should be field tested in a pre-excavated horizontal hole. See the next section (5.15) for details.

5.15 ADVANTAGES OF EARLY FIELD TRIALS

OBJECT

The objectives of a SIMPLE field trial are many. Instrumentation of the drilling motor could supply hard facts of machine-soil interaction rather than hypotheses. The practicality of pulling separate follower packages and mud pressure testing of ground stability could

be determined. Further publicity--implementation--could be given to both the excavation (pipelining) and exploration (tunneling) aspects of horizontal penetration. Hydraulic fracture models could be checked. The costs could perhaps be shared with private industry by coupling the field test with undergrounding of a pipeline or with other levels of government by coupling with the early exploration phase of a planned tunnel.

INSTRUMENTATION OF THE DRILLING PROCESS

Titan's horizontal rig and downhole equipment could be instrumented to monitor the environmental parameters during a 1000 to 2000 ft (300 to 600 m) bore. This instrumentation would be designed to obtain the following:

- Bit Torque/Soil Strength
- Normal Force/Soil Strength
- Fracture Pressure/Fracture Gradient
- Vibration/Soil Strength/Type and Drill Path and Equipment
- Head Losses Associated With Fines
- Transport/Annulus Size and Soil Type

In addition, DRILCO's thruster could be quickly modified to test its adaptability during excavation of the same hole.

EXPLORATION PACKAGES

Feasibility of exploratory follower packages could also be checked. First the difficulty of pulling such a package through a mudded passageway could be determined. Next simple combination of existing geophysical equipment could be field calibrated against boring records. Finally, expendable calipers could be placed to determine the feasibility of checking stand-up times with decreasing mud pressures.

IMPLEMENTATION

The field trials, when combined with a pipelining job, would publicize the present capabilities of horizontal boring. The instrumentation of the excavation equipment would advance knowledge necessary for increasing penetration distances for undergrounding of pipelines.

The field calibration of exploration techniques would advance sensing capabilities. Thus the two disciplines of pipelining and exploration could be advanced together, each growing more than if investigated separately.

COST SHARING

For industrial coupling, the costs of field research involved with mobilization, site preparation, preliminary exploration, crew familiarization with drilling in particular conditions, and demobilization could be shared with the industry paying for the eventual pipeline. Only costs resulting from field checking equipment and possible excavation of vertical holes or a second hole would accrue to the funding agency(ies).

For local public-agency coupling, the costs of site access and comparative vertical exploration results could be funded by the local agency. Horizontal boring and exploration costs would accrue to the funding agency.

The cost of this field test could vary widely but is estimated to cost $100,000 (RANK = highest of all except further amortizement of potential costs, resulting from poor exploration).

APPENDIX A

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APPENDIX B

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APPENDIX C

GLOSSARY OF SPECIALIZED TERMINOLOGY

Because of the extreme breadth of this study, terms were introduced which are peculiar to specialized disciplines. These terms may not be familiar to all those reading this report. This appendix defines a selection of the specialized terminology.

ACCURACY: The exactness with which an instrument or system performs.

ANNULAR SPACE: The space surrounding a cylindrical object within a cylinder. The space around a pipe in a borehole is often termed the annulus, and its outer wall may be either the wall of the borehole or the casing.

AZIMUTH or HEADING: The angle of the borehole direction, measured clockwise from north in a horizontal plane.

BENTONITE: A plastic, colloidal clay, largely made up of the mineral sodium montmorillonite, a hydrated aluminum silicate. For use in drilling fluids, bentonite has a yield in excess of 85 bbl/ton. The generic term "bentonite" is neither an exact mineralogical name, nor is the clay of definite mineralogical composition.

BIT SUB or SUB: A connecting joint that permits a change in thread form and decreases the possibility of damage to important pieces of equipment (i.e., a downhole motor).

BUILD ANGLE (α): Rate of angular change along a drill path measured in degress per 100 feet.

CIRCULATION: The movement of drilling fluid from the suction pit through pump, drill pipe, bit, annular space in the hole, and back again to the suction pit. The time involved is usually referred to as circulation time.

CIRCULATION, LOSS OF (or LOST): The result of drilling fluid escaping into the formation by way of crevices or porous media.

CIRCULATION RATE: The volume flow rate of the circulating drilling fluid usually expressed in gallons or barrels per minute.

COMMUNICATION or TELEMETRY: Transfer of information from the excavation equipment to the operator.

DIRECTIONAL CONTROL: See GUIDANCE.

DRIFT: Deflection of the bit off the intended path (independent of heading).

DRIFT ANGLE: See ELEVATION.

DRILLING MUD OR FLUID: A circulating fluid used in rotary drilling to perform any or all of various functions required in the drilling operation.

EARTH'S ANGULAR VELOCITY: A vector whose magnitude and direction define the earth's spin.

ELEVATION or DRIFT ANGLE: The vertical angle of the borehole direction, measured either from a horizontal or vertical plane, depending on instrument.

ENTRY POINT: Point on the earth's surface where the drill bit initially penetrates.

EQUIVALENT CIRCULATING DENSITY: For a circulating fluid, the equivalent circulating density in lb/gal equals the hydrostatic head (psi) plus the total annular pressure drop (psi) divided by the depth (ft) and by 0.052.

FILTER CAKE: Filter cake refers to the layer of concentrated solids from the drilling mud that forms on the walls of the borehole opposite permeable formations. Also called mud cake.

FILTER CAKE TEXTURE: The physical properties of a cake as measured by toughness, slickness, and brittleness.

G-SENSITIVITY: Gyro drift uncertainty which is proportional to acceleration (or gravity).

GUIDANCE or STEERING or DIRECTIONAL CONTROL: The act of changing course which involves both a control decision and a mechanical change in the excavating system.

GYRO DRIFT: The precession of the gyro spin axis resulting from applied torques.

HEADING: See AZIMUTH.

INSTANEOUS RADIUS OF CURVATURE: The radius of curvature along a spiral drill path measured at a particular point.

JET BIT: A drilling bit having nozzles through which the drilling fluid is directed in a high velocity stream.

KEY SEAT: That section of a hole, usually of abnormal deviation and relatively soft formation, which has been eroded or worn by drill pipe to a size smaller than the tool joints or collars. This keyhole type configuration will not allow these members to pass when pulling out of the hole.

KINEMATIC VISCOSITY: The kinematic viscosity of a fluid is the ratio of the viscosity (e.g., cp in g/cm - sec) to the density (e.g., g/cc) using consistent units. In several common commercial viscometers the kinematic viscosity is measured in terms of the time of efflux (in seconds) of a fixed volume of liquid through a standard capillary tube or orifice.

KINK: The "elbow" caused by a sharp change of direction in the bore.

KINK RADIUS OF CURVATURE: The smallest radius of curvature in an undulating section of the drill path.

LAMINAR FLOW: Fluid elements flow along fixed streamlines which are parallel to the walls of the channel of flow. In laminar flow, the fluid moves in plates or sections with a differential velocity across the front which varies from zero at the wall to a maximum toward the center of flow. Laminar flow is the first stage in a Newtonian fluid; it is the second stage in a Bingham plastic fluid. This type of motion is also called parallel, streamline, or viscous flow.

MUD: A water- or oil-based drilling fluid whose properties have been altered by solids, commercial and/or native, dissolved and/or suspended. Used for ciculating out cuttings and many other functions while drilling a well. Mud is the term most commonly given to drilling fluids.

MUD PIT: Earthen or steel storage facilities for the surface mud system. Mud pits which vary in volume and number are of two types: circulating and reserve. Mud testing and conditioning are normally done in the circulating pit system.

MUD PUMPS: Pumps at the rig used to circulate drilling fluids.

NAVIGATION or SURVEY: The identification of the location and orientation of a body with respect to a reference coordinate frame.

NEWTONIAN FLUID: The basic and simplest fluids from the standpoint of viscosity in which the shear force is directly proportional to the shear rate. These fluids will immediately begin to move when a pressure or force in excess of zero is applied. Examples of Newtonian fluids are water, diesel oil, and glycerine. The yield point as determined by direct-indicating viscometer is zero.

NONREPEATABILITY: The inability of an instrument to repeat readings for a series of identical inputs.

NORMALLY CONSOLIDATED CLAY: A clay which has experienced no greater vertical stress than that which exists.

NULL OFFSET or BIAS: Nonzero output for zero input.

PITCH: Rotation about a transverse body axis, horizontal only if roll is zero.

PRESSURE-DROP LOSS: The fluid pressure loss in a pipeline or annulus during flow: a function of the properties of the fluid and the condition of the pipe wall.

PLASTIC FLUID: A complex, non-Newtonian fluid in which the shear force is not proportional to the shear rate. A definite pressure is required to start and maintain movement of the fluid. Plug flow is the initial type of flow and only occurs in plastic fluids. Most drilling muds are plastic fluids. The yield point as determined by direct-indicating viscometer is in excess of zero.

RADIUS OF CURVATURE: Can be approximated as one-half the distance traveled times the cotangent of one-half the build angle.

RESOLUTION: The minimum increment distinguishable.

REYNOLDS NUMBER: A dimensionless number, N'_R, that occurs in the theory of fluid dynamics. The diameter, velocity, density, and viscosity (consistent units) for a fluid flowing through a cylindrical conductor are related as follows:

$$N'_R = (\text{diameter})^n\ (\text{velocity})^{2-n}\ (\text{density}) / (\text{viscosity})$$

$$\text{or} \quad = D^n V^{2-n}/K^*$$

(See Appendix F)

The number is important in fluid hydraulics calculations for determining the type of fluid flow, i.e., whether laminar, or turbulent. The transitional range occurs approximately from 2000 to 3000; below 2000 the flow is laminar; above 3000 the flow is turbulent.

ROLL: Rotation about a longitudinal body axis by an instrument.

STEERING: See GUIDANCE.

STUCK: A condition whereby the drill pipe, casing, or other devices inadvertently become lodged in the hole. May occur while drilling is in progress, while casing is being run in the hole, or while the drill pipe is being hoisted. Frequently a fishing job results.

SUB: See BIT SUB.

SURVEY: See NAVIGATION.

SYSTEMATIC ERRORS: Predictable by physical modeling.

TELEMETRY: See COMMUNICATION.

TOOL JOINT: A drill-pipe coupler consisting of a pin and a box of various designs and sizes. The internal design of tool joints has an important effect on mud hydrology.

TORQUE: A measure of the force or effort applied to a shaft causing it to rotate. On a rotary rig this applies especially to the rotation of the drill stem in its action against the bore of the hole. Torque reduction can usually be accomplished by the addition of various drilling-fluid additives.

TORQUING RATE: The precession rate of a gyro in response to an applied torque.

TRICONE BIT: A type of rock bit in which each of three toothed, conical cutters is mounted on friction reducing bearings. The bit body is fitted with nozzles--jets--through which the drilling fluid is discharged.

VISCOSITY: The internal resistance offered by a fluid to flow. This phenomenon is attributable to the attractions between molecules of a liquid, and is a measure of the combined effects of adhesion and cohesion to the effects of suspended particles, and to the liquid environment. The greater this resistance, the greater the viscosity.

WASHOVER PIPE: An accessory drilled over the outside of tubing or drill pipe to clean out the annular space and permit recovery or movement.

WATER TABLE: The underground level at which water is found, pore pressure is atmospheric.

YAW: Rotation about a body axis normal to pitch and roll.

YIELD VALUE: The yield value (commonly called "yield point") is the resistance to initial flow, or represents the stress required to start fluid movement. This resistance is due to electrical charges located on or near the surfaces of the particles. The values of the yield point and thixotropy, respectively, are measurements of the same fluid properties under dynamic and static states. The Bingham yield value, reported in lb/100 sq. ft., is determined by the direct-indicating viscometer by subtracting the plastic viscosity from the 300 rpm reading.

APPENDIX D

EXCAVATION EQUIPMENT FOR MANEUVERABLE HORIZONTAL PENETRATION

D.1 INTRODUCTION

Horizontal directionally controlled drilling is currently an art. As a result of the embryonic state of this particular type of drilling, much of the information for this section has been gathered by telephone conversations, letters, and personal visits.

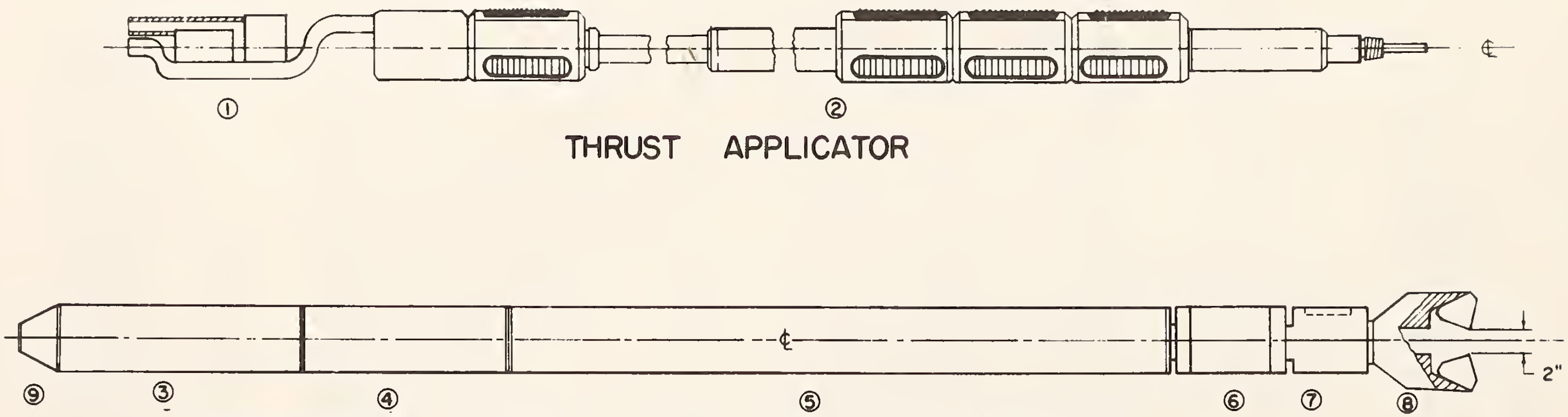
This appendix presents on-shelf mechanical equipment, specifications, and techniques which are currently applied or have on-shelf potential for application in soft-ground, horizontal boring. An initial listing of all possible current and novel penetration techniques applicable to both soft-gound and hard-rock horizontal hole is presented in another D.O.T. report, entitled Improved Subsurface Investigation for Highway Tunnel Design and Construction (Ash, 1974). This presentation will begin where the previously mentioned report concluded and treats only mechanical penetration. Four major components of the maneuverable penetration system will be discussed: (1) downhole motors, (2) downhole thrust applicators, (3) directional control equipment, and (4) drill bits.

Figure D.1 presents the scaled drawings of the two main types of penetrator systems synthesized as a result of this investigation.

Two principal methods of developing normal force at the bit were synthesized. The mandrel system is similar to conventional drilling in a horizontal direction. However, the drill steel does not rotate except to steer, and the bit is rotated by a downhole motor. Course changes are effected by changing the ratios of normal force to bit rotation and rotation of the eccentrically mounted bit and motor. The thruster system develops normal force by thrusting against anchors pressed against the hole and is connected to the surface with flexible cable. Course changes are effected by deflecting jacks (shoes) near the bit. Both of these methods can be combined with various downhole motors, bits, navigation, sensing and communication subsystems.

D.2 DOWNHOLE MOTORS

Four downhole motors are discussed in this appendix. They have either been previously applied in directional drilling or specifically in horizontal directional drilling in soft ground. These four motors are: the Dyna-Drill, the turbo-drill, the electric motor, and the hydraulic motor.



COMPONENTS : ATTACH TO DRILL PIPE OR THRUSTER

The mandrel is a non-rotating drill pipe of smaller diameter than the hole. It transfers thrust from the uphole drilling platform to the illustrated downhole components, and is protected by the washover pipe. See page N-10 for the geometrical details of mandrel and washover pipe and N-2 and N-19 for the platform.

	COMPONENTS
1	Downhole hyd valving
2	Thrust applicator
3	Electronic package
4	Orientating motor
5	Hyd drill motor
6	Deflection Shoe
7	Bit sub
8	Tricone core bit
9	Bent sub

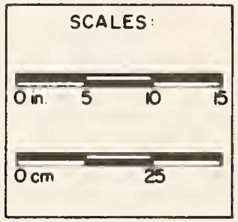


FIGURE D.1 SCALED DRAWING : PENETRATOR SYSTEMS

DYNA-DRILL

Dyna-Drill is the most popular downhole directional motor in the oil industry today. It is a positive displacement hydraulic motor which operates on the principle of a reverse Moyno® pump and is shown in Figure D.2. The obround, spiral stator is made from synthetic rubber which is compressively fit to reduce fluid slippage. The stator houses the solid steel rotor which has a longitudinal sinusoidal shape and rotates eccentrically within the stator. The upper end of this rotor is free while the bottom end is attached to the connecting rod. The connecting rod consists of universal joints that convert the eccentric motion of the rotor to concentric motion required for the drive shaft. The bit sub at the bottom of the drive shaft is the only external moving part.

As drilling fluid is pumped downward along the spiral path between the stator and the rotor, the rotor is displaced and rotated within the stator. The rotor in turn powers the connecting rod, drive shaft, bit sub and bit. Hydraulic horsepower and torque output are a function of the pressure loss during flow through the motor (ΔP). The operational rpm can also be estimated from ΔP.

The Dyna-Drill size most adaptable to horizontal boring in soft ground has been the 1-3/4 in (4.45 cm) O.D. downhole motor used in drilling pilot holes for underground pipelines beneath rivers (Emery, 1975). As a result of the experience gained from these river crossings, Dyna-Drill has designed a 2-3/8 in (6.03 cm) O.D. downhole motor which will produce more torque, smaller flow rate and slightly greater drop in ΔP as the 1-3/4 in (4.45 cm) O.D. motor (Tschirky, 1975). The 2-3/8 in (6.03 cm) model is approximately 8 ft (2.4 m) long and has the capability of boring a 4-1/2 in (11.43 cm) hole. This particular Dyna-Drill will be an optimal motor for horizontal drilling in soft ground because of its relative maneuverability, lightness in weight, and low fluid flow requirements.

Two sizes of the Dyna-Drill have been considered in the final equipment synthesis. The specifications for these two devices are listed in Table D.1

Table D.1 Dyna-Drill Specifications

O.D. (in)	Length (ft)	ΔP (psi)	RPM	GPM	HP	Wt. (lb)	Torque (ft-lb)	Hole Size
2-3/8	8.3	600	1000	25	6	75	30	4-1/2
6-1/2	19.6	250	305	250	28	1422	467	12

1 in. = 2.54 cm.
1 ft. = 0.305 m
1 psi = 6.9 kN/m^2

1 lb. = 0.454 kg
1 ft. - lb. = 0.138 kg - m

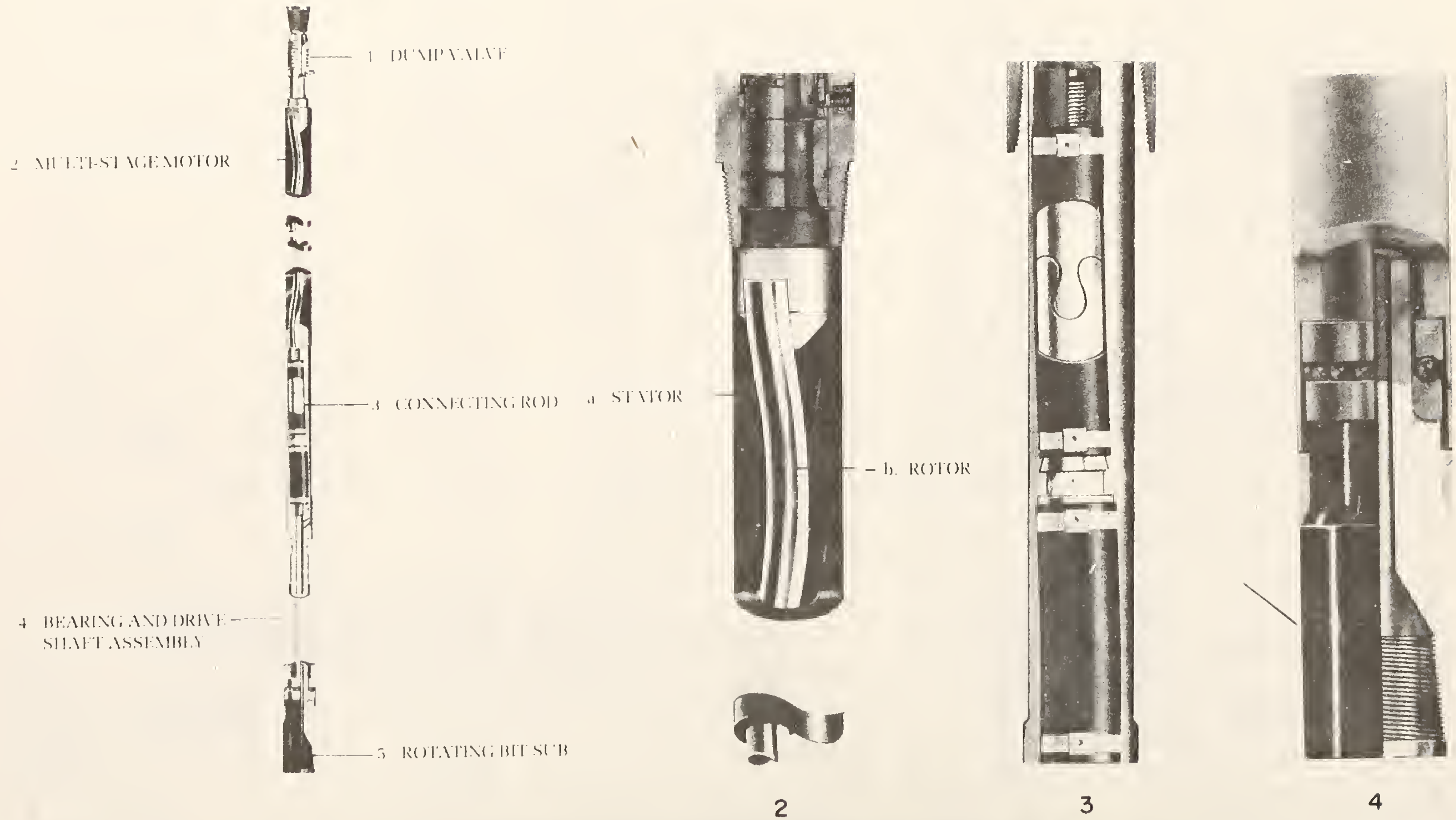


FIGURE D.2 DYNA - DRILL (After Dyna-Drill, 1975)

TURBO-DRILL

A turbo-drill is a multi-stage, axial mud turbine illustrated in Figure D.3 and can be employed in straight and directional drilling. Each stage of the motor consists of a rotor which is attached to the axial shaft and a fixed stator secured to the housing. A typical 5 in (12.7 cm) diameter turbo-drill will contain 86 stages in line (Eastman, 1969). The fluid velocity or pressure loss across the turbine will determine the torque and the horsepower output.

The turbine motor has two other basic components besides the series of turbine stages. They are a replaceable bearing section shown in Figure D.3 and a rotating bit sub.

Several difficulties arose in the initial application of a turbine motor to directional drilling. The operating rpm of this motor is approximately 1000 rpm. Therefore, tricone bits could not be used because the high rpm greatly reduced the bearing life. The high rpm's and relatively low horsepower output tended to result in the turbine motor stalling in soft, sticky clay. When the turbo-drill stalls, there is no direct indication of this condition as there was with the Dyna-Drill.

The turbo-drill is also sensitive to bending because of the required alignment between the rotor and stator blades. Any bending resulting from a sharp build angle, would bind or damage the turbine.

For the reasons stated above, along with the excessive weight and length of the turbo-drill, this downhole motor is not considered in the final equipment design recommendations. Table D.2 lists the various specifications for two sizes of turbo-drills available from Eastman Whipstock, Incorporated.

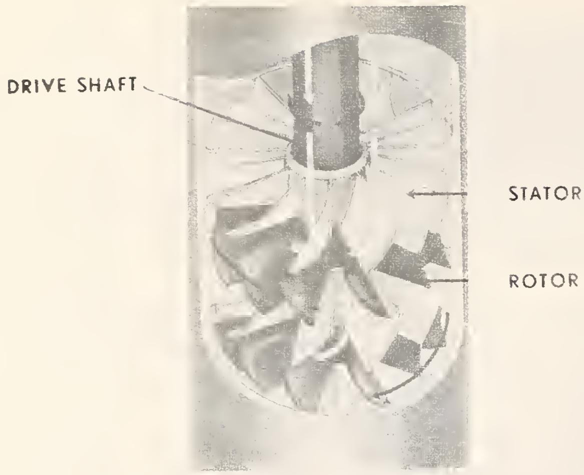
Table D. 2 Turbo-Drill Specifications

O.D. (in)	Length (ft)	ΔP (psi)	RPM	GPM	Stages	HP max	Wt (lb)	Stall Torque (ft-lb)	Hole Size (in)
5-1/8	18-1/2	328	780	250	60	26	750	272	7-7/8
6-3/4	23-3/4	369	813	400	76	49.8	1985	591	7-7/8

ELECTRIC MOTOR

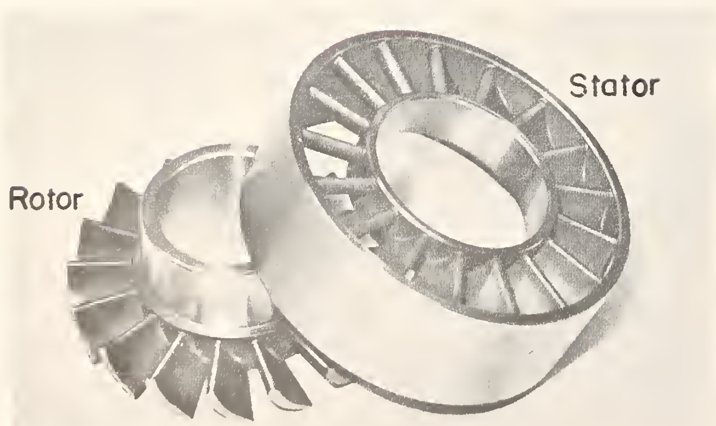
Drilling with an electric motor is not new. They were first used in the early 1950's in Russia. The length of these early electrodrills ranged from 36-42 ft (11-13 m) with power requirements ranging from 100-200 kw. The electric motor considered in this investigation is an order of magnitude smaller in size and power requirement.

(1 in. = 2.54 cm; 1 ft. = 0.305 m; 1 psi = 6.9 kN/m^2) (1 lb. = 0.454 kg; 1 ft. - lb. = 0.138 kg - m)



TURBINE SECTION OF
TURBO - DRILL
(After U. of Texas, 1972)

REPLACEABLE
BEARING SECTION
(After Eastman, 1969)



TURBINE ROTOR AND
STATOR
(After Eastman, 1969)

FIGURE D.3 TURBO - DRILL TURBINE COMPONENT PARTS

Contintental Oil Company (CONOCO) has adopted an ordinary submersible pump motor to drill 6 in (15 cm) diameter holes in soft coal (Dahl, 1975). This submersible pump motor is made by Century Electric Motor Company in Gettysburg, Ohio. Specifications for this motor (DeGrand, 1975) are listed in Table D.3 and are drawn schematically in Figure D.4.

The electric motor must be coupled with a reduction gear box because of the high output rpm's of the motor. A suitable planetary type gear box was designed by Reda Pump Company for one of their submersible motor pumps with available gear ratios varying from 28.51:1 to 3.165:1 for driving the drilling bit at 121-1095 rpm. The outside diameter of this unit is 4-1/2 in (11.4 cm) with a length of about 2 ft (0.6 m). It weighs 100 lbs (45.3 kg).

Three important factors should be considered if this electric motor is adapted to drilling in soft ground below the water table. Quick trip overload protectors should be added in all three legs of the three phase motor. These protectors will prevent lock-up of the motor if it stalls from an overload and is not restarted immediately. Secondly, there exists a possibility of electrical shorting because of water leakage. Thirdly, a constant flow of drilling fluid over the outside of the motor should be maintained to prevent overheating. The minimum cooling flow requirement is a gallon/minute/HP (approximately 5 GPM or 0.3 l/sec for the above example) which is easily satisfied.

Table D.3 lists the important specifications for the Century submersible motor.

Table D.3 Century Electric Motor Specifications

O.D. (in)	Length (ft)	Voltage	Amps	HP	RPM	Wt (lb)	Hole Size (in)
3-11/16	2.7 (4.7 with gear box)	460	10.0	5	3450	50	7

(1 in. = 2.54 cm.)
(1 ft. = 0.305 m.)
(1 lb. = 0.454 kg.)

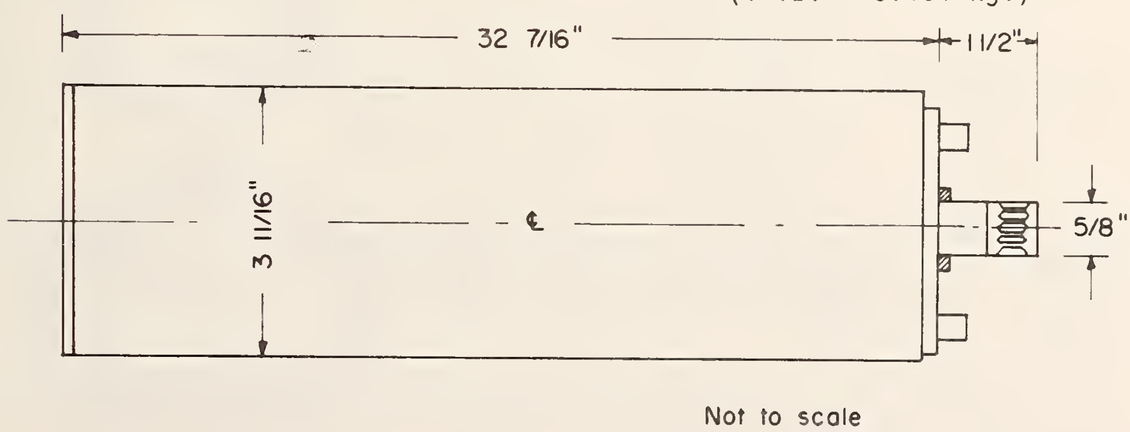


FIGURE D.4 CENTURY ELECTRIC MOTOR (SCHEMATIC)

HYDRAULIC MOTOR

In an attempt to find a short, small diameter and lightweight hydraulic motor that could be adapted to the DRILCO thrust applicator, Continental Oil Company (CONOCO) had the W. H. Nichols Company in Waltham, Massachusetts, make a special order gerotor pump motor (Coffey, 1975).

The result, a gerotor, is an internal gear, positive displacement pump motor. Any type of drilling fluid can drive this motor. Because of the motor's concentric rotation, the rotational vibration of the gerotor is small compared to the Dyna-Drill.

The motor shown in Figure D.5 consists of an inner and outer gerotor and an eccentric locator-ring. The inner gerotor always has one tooth less than the outer gerotor. This gerotor is placed in a casing or frame which provides housing and porting. Output power is a function of the number of gerotor units that are connected in series. For the design characteristics in Table D.4, the motor had 16 sets of gerotor units in series.

The principle of operation of the gerotor is shown in Figure D.5. Inlet ports in step 1 allow drilling fluid to fill a volume equal to the missing tooth. The toothed elements are mounted on fixed centers but turn eccentric to each other with the inner gerotor being mounted to the drive shaft. As the gerotors turn through step 2 and 3, the chamber in which the fluid is carried decreases in size. At step 4, the fluid is forced out the discharge port into the next gerotor in series.

Table D.4 lists the important specifications for the particular motor designed for CONOCO.

Table D. 4 Hydraulic Motor Specifications

O.D. (in)	Length (ft)	ΔP (psi)	RPM	GPM	HP	Wt (lb)	Torque (ft-lb)	Hole Size (in)
5	4	570	300	30	10	25	175	7

(1 in. = 2.54 cm; 1 ft. = 0.305 m; 1 psi = 6.9 kN/m^2; 1 lb. = 0.454 kg; 1 ft. - lb. = 0.138 kg - m)

D.3 DOWNHOLE THRUST APPLICATORS

A thrust applicator is a relatively short downhole device which provides a base for reactive torque and normal force for a drilling motor or a compacting mechanism. This appendix will elaborate upon four such devices: the DRILCO thrust applicator, NURAT, U.S. Navy Polytordial Tunneler, and WORM™*.

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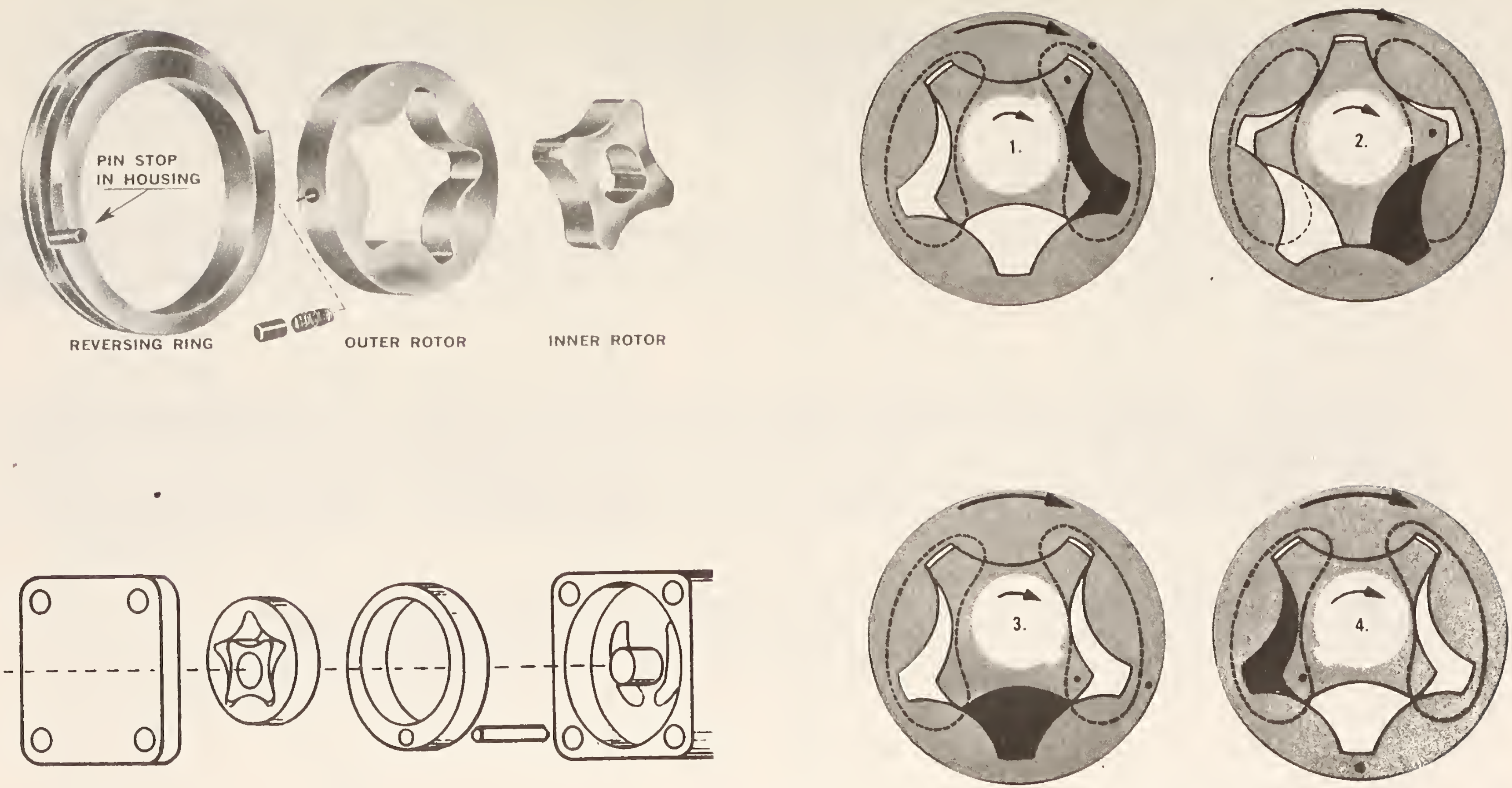
* The name WORM is the trademark (TM) which the inventor intends to apply to this system. It is so identified to preclude its assuming a generic connotation (Still, 1975).



a) PARTS

b) OPERATION

FIGURE D.5 GEROTOR
(After Nichols, 1975)

DRILCO THRUST APPLICATOR

The thrust applicator manufactured by DRILCO in Midland, Texas, is a fully developed and operational thruster invented by Jack Kellner. This device can load and advance any type of drilling motor forward or backward. Most of its application to date has been in horizontal drilling, primarily in coal, with the longest hole being 800 ft (244 m) at a diameter of 6 in (15.2 cm) (Dahl, 1975). Figure D.6 shows parts for the 2-3/4 in (7.0 cm) version of the DRILCO thruster. Figure D.1 shows the assembled mechanism.

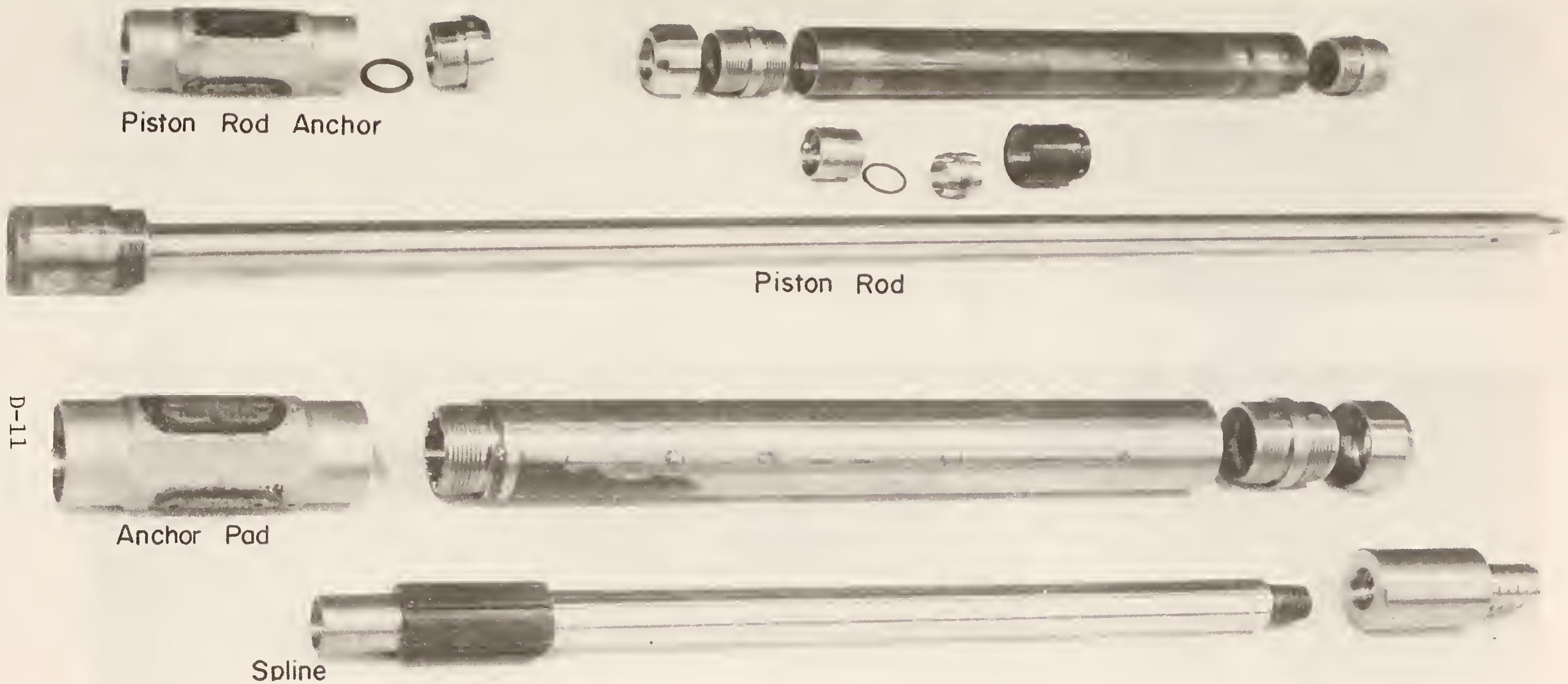
The thruster is a double-acting cylinder with a hollow piston rod running through both ends. There are two anchor sets: the cylinder anchors, and the piston rod anchors. The anchor pads shown in Figure D.6 are made of steel with cross ribbing to improve their frictional characteristics.

A hard elastic rubber is molded to the metal body of the anchor pad, including the entire internal circumference of the anchor sleeve. This rubber serves two purposes. First, it provides a means for returning the anchor pad to its original position after the hydraulic pressure is released. It also prevents particles from being caught underneath the anchor pads as they contract for repositioning. As many as three sets of anchor units can be attached to the thruster in the cylinder anchor section (present design), while at the present time only one set of anchor pads can be attached at the piston anchor section.

In order to prevent rotation, there is a spline between the extension piston rod and anchor cylinder section.

The operation sequence of this thruster is as follows: (1) pressure is applied to the cylinder anchors, securing them to the drill hole wall; (2) pressure is then applied to the "out-hole" piston which moves the piston rod forward, thereby providing forward thrust to the drilling motor as it advances in the hole (the advance is limited by the stroke of the device); (3) at the end of the stroke the cylinder must be reset, therefore the piston rod anchors are set against the drill hole wall; (4) next, pressure is released from the cylinder anchors which retract; (5) pressure is then applied to the "in-hole" side of the piston, forcing the cylinder toward the bit one stroke length. The thruster is then in position for another stroke. The hydraulic power unit is designed so that the resetting operation is completed automatically in 10-12 seconds (Kellner, 1974). The sequence can be reversed to back the thrust applicator out of the hole under its own power.

The auxiliary equipment located on the surface for this thrust applicator include 3-5 hoses which are attached to the rear of the device, a 5 HP hydraulic power unit, and a means for powering the drilling motor which can be either hydraulic (water or mud) downhole motor, modified hydraulic motor, or an electric motor. Figure D.7 illustrates the surface equipment setup and required operating personnel. This picture was taken at the DRILCO test site in Midland, Texas.



(1 in. = 2.54 cm)

FIGURE D.6 2 3/4 IN. O.D. DRILCO THRUST APPLICATOR
(Courtesy of Drilco Industrial)

FIGURE D.7 OPERATIONAL TEST OF DRILCO THRUST APPLICATOR
(After DRILCO, 1975)

Presently, DRILCO has the ability and experience to produce a thrust applicator which would be more compatible to soft ground operation than the current models. Future research and development for DRILCO in this area will obviously be a function of the market's demand.

Table D.5 lists the important specifications for the thrust applicator.

Table D.5 DRILCO Thrust Applicator Specifications

O.D. (in)	Length (ft)	Stroke (in)	Weight (lb)	Hole Size (in)
2-3/4	7.6	18	80	3-1/8
5-3/4	10.6	30	200	6

(1 in. = 2.54 cm; 1 ft. = 0.305 m; 1 lb. = 0.454 kg)

NURAT

NURAT is an acronym for Newcastle University Root Analogue Tunneller. It is a combination penetrator and thrust applicator similar to the Pneuma-gopher. NURAT was invented by Dr. Daniel Hettiaratchi at the University of Newcastle upon Tyne at Newcastle upon Tyne, England under the auspices of the British Gas Corporation (Hettiaratchi, 1974). Since conception, the British Gas Corporation has taken over the development and testing of this device (Spearman, 1974).

Dr. Hettiaratchi and the British Gas Corporation have released only limited information about the device because of their desire to protect pending patent applications on NURAT. A schematic drawing from the University of Newcastle is shown in Figure D.8.

NURAT was the result of several years of study by Dr. Hettiaratchi involving the mecanism by which roots grow in soil. When the pressure at the tip of the root prohibits extension, the root expands radially outward hence stress relieving the area directly in front of the root tip which then allows the root to grow. NURAT operates in a similar manner. As the anchor pads are extended radially outward, normal stresses are reduced at the tip of the device. The cone then thrusts ahead of the main body, compacting the soil around the cone.

The operating model of NURAT is approximately 3.3 ft (1 m) long and creates a hole about 6 in (15 cm) in diameter. The penetration rate of this prototype device is about 20 ft (6 m) per hour. There is no directional control device for the NURAT prototype. Suitable means to control the direction of NURAT must be found to make the system practical. More information should become available in 1976. The present development conducted by the British Gas Corporation is focused on the general design specifications (Spearman, 1974) in Table D.6.

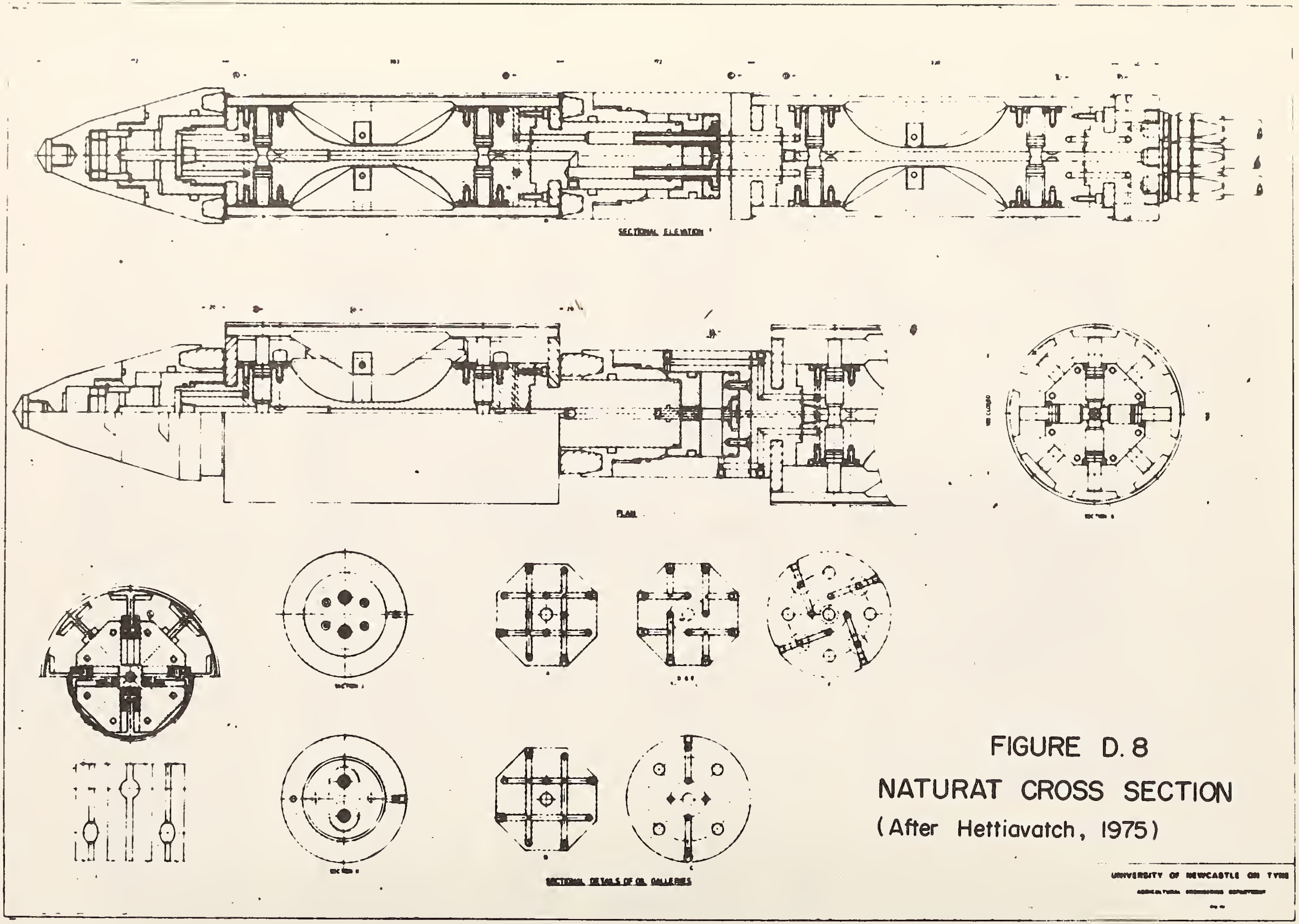


FIGURE D.8
NATURAT CROSS SECTION
(After Hettiavatch, 1975)

Table D.6 NURAT Design Specifications

O.D. (in)	Length (ft)	Weight	Power Source	Rate of Penetration	Comments
		Capable of being handled by two persons	Mobile Hydraulic Power Pack	60 ft/hr in sand or clay	Should have ability to reverse direction

(1 in. = 2.54 cm; 1 ft. = 0.305 m)

BRITISH GOVERNMENT POST OFFICE DUCTMOTOR

The British Post Office has designed the ductmotor to crawl through utility ducts. The following design criteria were imposed: the ductmotor had to be able to pass through water, mud, and silts, around bends and maneuver up and down inclines. In addition, it had to be able to operate over a distance of 1800 ft (549 m), pulling a coaxial cable without cable damage (Deadman and Slight, 1965).

The ductmotor has two air bags, one forward and one aft, connected by an extension arm. The device has an inchworm motion such that, when the after air bag is inflated, securing the after section, the arm extends forward the distance of its stroke, then the forward bag inflates and secures itself to the tunnel wall while the after bag deflates and the arm contracts. This process is then repeated.

To date this ductmotor has only been used in cable and utility ducts. However, the principle of operation is similar to the previously described DRILCO thrust applicator. The use of air bags for an anchoring mechanism is a valuable concept when penetrating soft ground, as tunnel wall disturbance would be greatly reduced. However, the equipment would have to incorporate a provision to allow return of the drilling fluid to the surface. With some modifications, the ductmotor could have the potential of being adapted as a thruster for soft ground horizontal penetration.

U.S. NAVY POLYTOROIDAL TUNNELING THRUSTER

The Civil Engineering Laboratory at Port Hueneme, California has conducted a feasibility study on the application of a vermiculating tunneling thruster to horizontal drilling (Williams and Gaberson, 1973).

A vermiculating or earthwormlike motion traverses a contacting surface with a longitudinal wave in the direction of motion by cyclically expanding and contracting a set of toroids as shown in Figure D.9a. The vermiculating motion is controlled by a system of cyclic timers in combination with a solenoid valving system. This device was designed to penetrate in a rock, clay, or sand medium using a cutting or boring device while providing a firm base for high thrust as a result of using a large contact surface.

The toroids squeeze against the tunnel wall and remain in position due to the frictional characteristics of the soil media. The thrust provided by each toroid was calculated using, $P = \pi Dwp\mu$, where D is the toroid diameter, w is the surface contact width, p is the inflation pressure, and μ is the coefficient of friction of the soil. This is the same relationship as the Mohr-Coulomb failure criteria (i.e. $\tau_{ff} = \sigma_1 \tan \phi$) for cohesionless soils. If both sides of the Mohr-Coulomb equation were multiplied by the contact area, then the resulting force would be maximum thrust available from the thrust device.

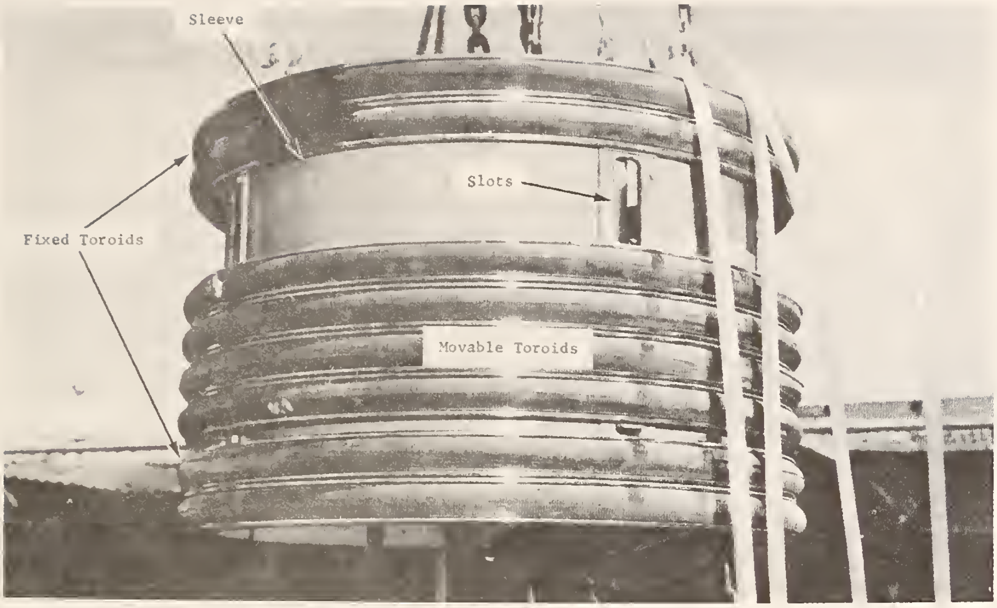
The operation of the polytoroidal thruster is illustrated in Figure D.9b. In step (1) the most forward toroid is deflated, in step (2) the device has advanced one step because the forward bag expanded simultaneously while the after bag deflated. In step (3) the middle bag deflated while the after bag was inflating. Finally, in step (4) the forward bag is deflated. This then completes the cycle. With each cycle, the thruster moves forward.

Preliminary experimental tests verified that the device was feasible. These results initiated a search for material to make the toroids stronger, more durable, and more flexible. The internal working pressure was set at 10-50 psi(69-315 kN/m^2) while other design criteria included a cyclic inflating/deflating life of 10,000 cycles, low weight-to-strength ratio, low permeability to gases, and a high resistance to an adverse environment.

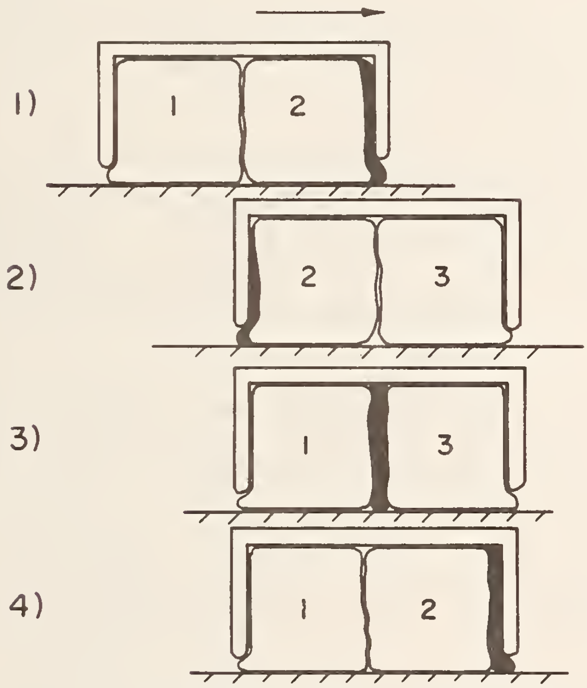
The result of this industrial search for a suitable toroid concluded that bladders had to be custom made. "The technology and the materials required to fabricate such bladders are available commercially (Pal and Gaberson, 1974)." However, the purchase cost of these bladders was considered noneconomical.

In a test using bicycle inner tubes as toroids(Figure D.9), the model was able to lift 600 lb(272 kg).

Because of insufficient funding, this particular project concluded at the feasibility stage. Recently, interest has been renewed in applying this principle to horizontal drilling. However, it is being considered for large diameter tunnel boring machines and not for a small diameter exploration hole.



a) EXPERIMENTAL MODEL



b) OPERATIONAL SEQUENCE

FIGURE D 9 U.S. NAVY POLYTOROIDAL THRUSTER
(After Williams & Gaberson, 1973)

If a method were developed for drilling mud to bypass the circumferential, flexible anchoring tubes, this type of thrust applicator could be successful because of its high contact area and its inherent ability to limit side wall damage due to anchoring.

WORM™

WORM (Rubin, 1974) is an acronym for Wheel-less Orthogonal Reaction Motor which is a downhole drilling system, shown in Figure D.10, invented by William Still of Aerospace Industrial Associates, Incorporated. This design approach solves two major and costly problems in drilling horizontally at long distances. First, like the previous thrusters, it provides a constant force at the bit, independent of the distance along the drill hole, and secondly it provides adequate maneuverability and orientation within the system so that it can function continuously without stopping for a survey (Still, 1975).

Presently, the WORM is still in the embryonic stages of development and the principle of operation has only been tested with a small model. No prototype has been built or tested in a subsurface environment.

The major design difference between the WORM and a thrust applicator is the replacement of the conventional individual anchor pads with elastomeric vector force cells, as shown in Figure D.12. The WORM, then, is an advanced form of the same concept presented in the section on the U.S. Navy Polytoroidal Tunneler. The locomotion principle applied here is the vermiculating or worm-like motion.

The WORM has two types of vector force cells, an axial and radial cell. The axial cell expands and applies force parallel to the axis of the borehole with insignificant radial expansion. The radial cells then expand radially outward from the borehole axis to provide contact surface for anchoring. The choice of an elastomer for the cell material must allow for cyclic expansion without excessive damage to the drill hole wall.

Directional control of this device is accomplished by controlling the degree of parallelism between the various muscle units. "A controlled lack of parallelism will force the WORM body to swing into an arc of fixed radius of curvature (Still, 1975)."

The WORM concept has many positive aspects to it, however since it has not been built as a prototype and field tested, it was not considered in the final equipment design.

D.4 DIRECTIONAL CONTROL EQUIPMENT AND TECHNIQUES

BENT DEFLECTING AND/OR ORIENTING SUB

A "sub" in "oil patch" parlance is a connecting joint. A bent sub is a short connecting joint with the upper threads cut concentric with

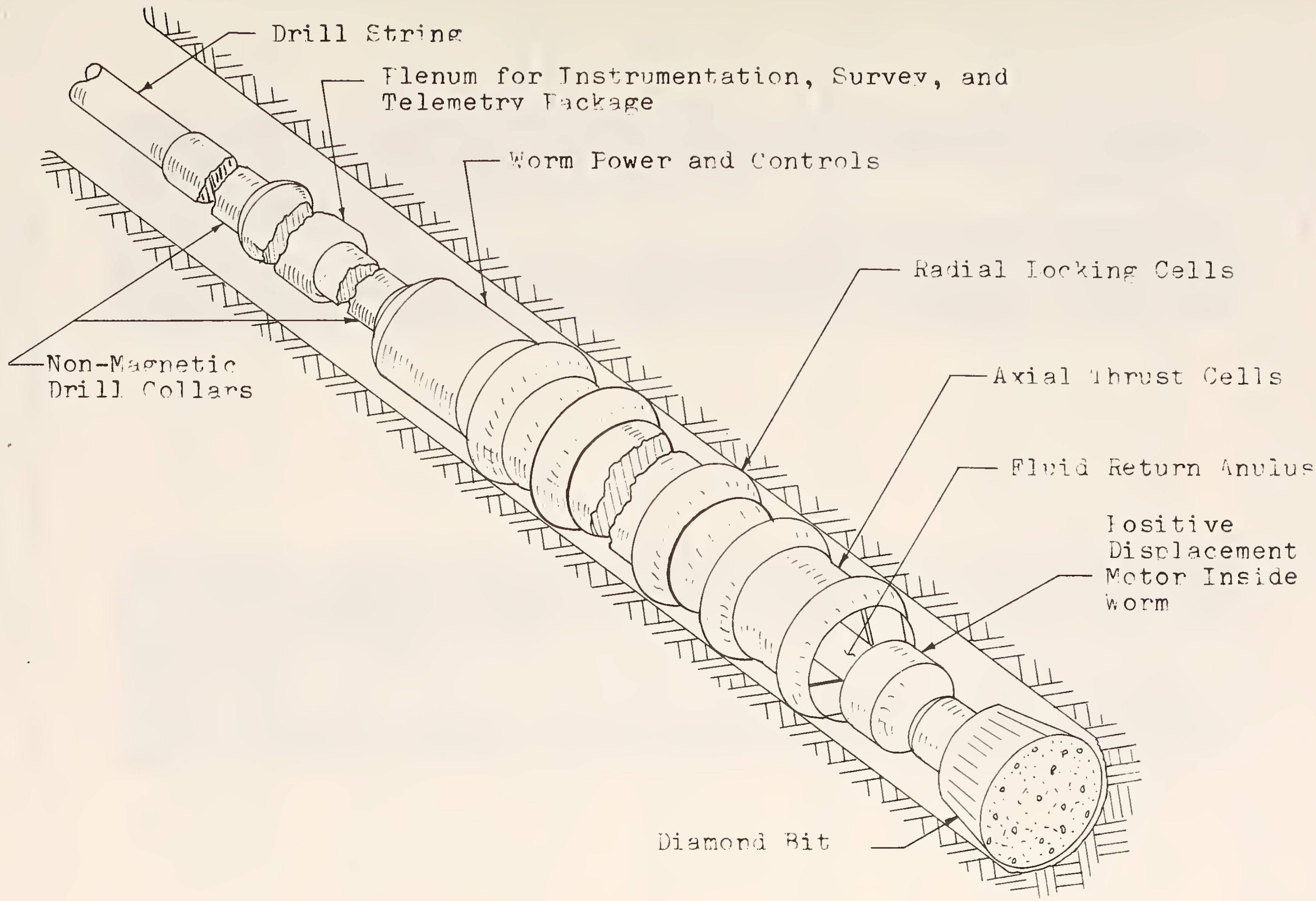


FIGURE D.10 WORM™ (After Still, 1975)

the axis of the sub body while the lower threads are cut concentric to an axis inclined from 1^{o} to 3^{o} at $1/2^{o}$ increments from the sub axis as shown in Figure D.11. The downhole motor faces the direction in which the sub is bent. By attaching a bent sub to a downhole motor, a smooth arc of curvature can be drilled as compared to the series of abrupt "dog-legs" which are associated with the familiar whipstocking techniques.

The radius of this smooth arc is established by the selection of the degree of bend in the bent sub. When a normal force is applied to the drill string, a bending moment is induced at the bent sub which results in reactive side force at the drill bit which causes the bit to deviate in the direction of the motor face. Therefore, the bent sub orients the drill bit in the desired direction of deviation. The drill pipe must be rotated in order to orient the face of the bit in a direction. This rotation must account for the desired direction of deviation, the reactive torque of the motor and twisting of the pipe.

ARTICULATED SUB

An articulated sub is a bendable sub with a hydraulically adjustable angle capability. Bowen Tool, Inc. in Houston Texas, manufactures the articulated sub and refers to it under the trade name of Dyna-Flex^{R}.

The Dyna-Flex has been developed to operate with any air-operated or hydraulic downhole motor and allows the motor to be selectively operated either as a straight or directional drilling tool. The Dyna-Flex bent sub is located directly above the downhole motor in the same position as a fixed-angle bent sub (see Figure D. 11).

To articulate the sub a knuckle joint is locked into the desired bend by insertion of the proper size locking probe. Under the present design, directional angle can range from 0^{o} to 2^{o} in $1/2^{o}$ increments. The diameter of the locking probe limits the angle at which the tool can be bent. If the angle is to be changed, the probe must be retrieved and a different diameter probe is positioned in the tool. When operating with a down-hole mud motor, the probe is pumped into position and retrieved with a Wire Line Overshot. When a Mule Shoe Orienting Sub Assembly is used for surveying, a special probe assembly must be acquired (Bowen, 1972).

The Dyna-Flex Bent Sub offers certain advantages. The directional angle can be changed in the drill hole without pulling the entire drilling assembly out of the hole as in the case of a fixed-angle bent sub. By changing probe sizes, the downhole assembly can be run into or withdrawn from a drill hole in the straight mode, thereby reducing sidewall damage.

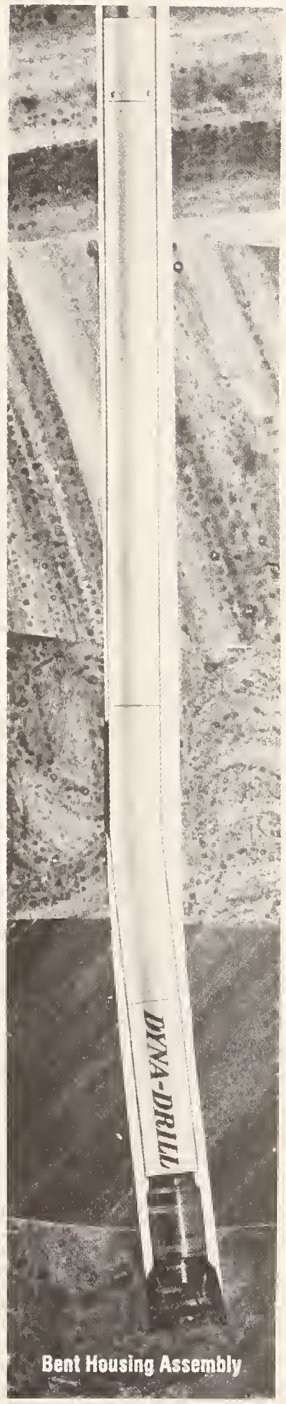


FIGURE D.11 BENT SUB AND BENT HOUSING ASSEMBLIES
(After Dyna - Drill Handbook, 1975)

There are several limitations involved in the use of Dyna-Flex. The smallest diameter presently available is 5 in(12.7 cm) O.D. However, the Bowen Tool Company has the ability to produce a 3-1/2 in(8.8 cm) O.D. Dyna-Flex if there is a demand for it. Also, drilling must stop during locking probe changes.

BENT HOUSING

This deflection device is only available on a Dyna-Drill where the flexible U-joint connecting rod permits a bend in the motor housing (see Figure D.13). The angles of bend are $0^{o}45'$, 1^{o}, $1^{o}15'$, $1^{o}30'$, and $1^{o}45'$ and are limited by the internal part clearances. A few of the advantages to this type of configuration are: (1) the bend is closer to the bit, thus the section between the bend and the bit is more rigid which results in less dissipation of the bending moment and side force effects on the bit, (2) the rate of angle change along the length of the drill hole is larger than with the bent sub and, (3) the amount of hole damage may be less than with the bent sub.

DEFLECTION SHOE

This particular deflection device was designed and tested by the Continental Oil Company (CONOCO) as a component for their horizontal directional drilling system (Dahl, 1975). Because CONOCO has a patent application pending on this device, the level of information is restricted so as not to infringe on their proprietary rights.

The deflection shoe, shown in Figure D.12, is extended by pressurizing an extension piston. Upon release of the pressure the piston is returned to its original position by return springs. The deflection shoe forces the bit against the hole in the direction of desired deviation. Since the deflection shoe is a directional with respect to its extension, a down-hole motor is required to orient the shoe. The hydraulic controls are located on the surface.

CONOCO's orientating motor is hydraulically controlled and can rotate the deflection shoe in 4^{o} increments (Edmond, 1975). The position of the deflection shoe is fixed by angular reference to the navigation package.

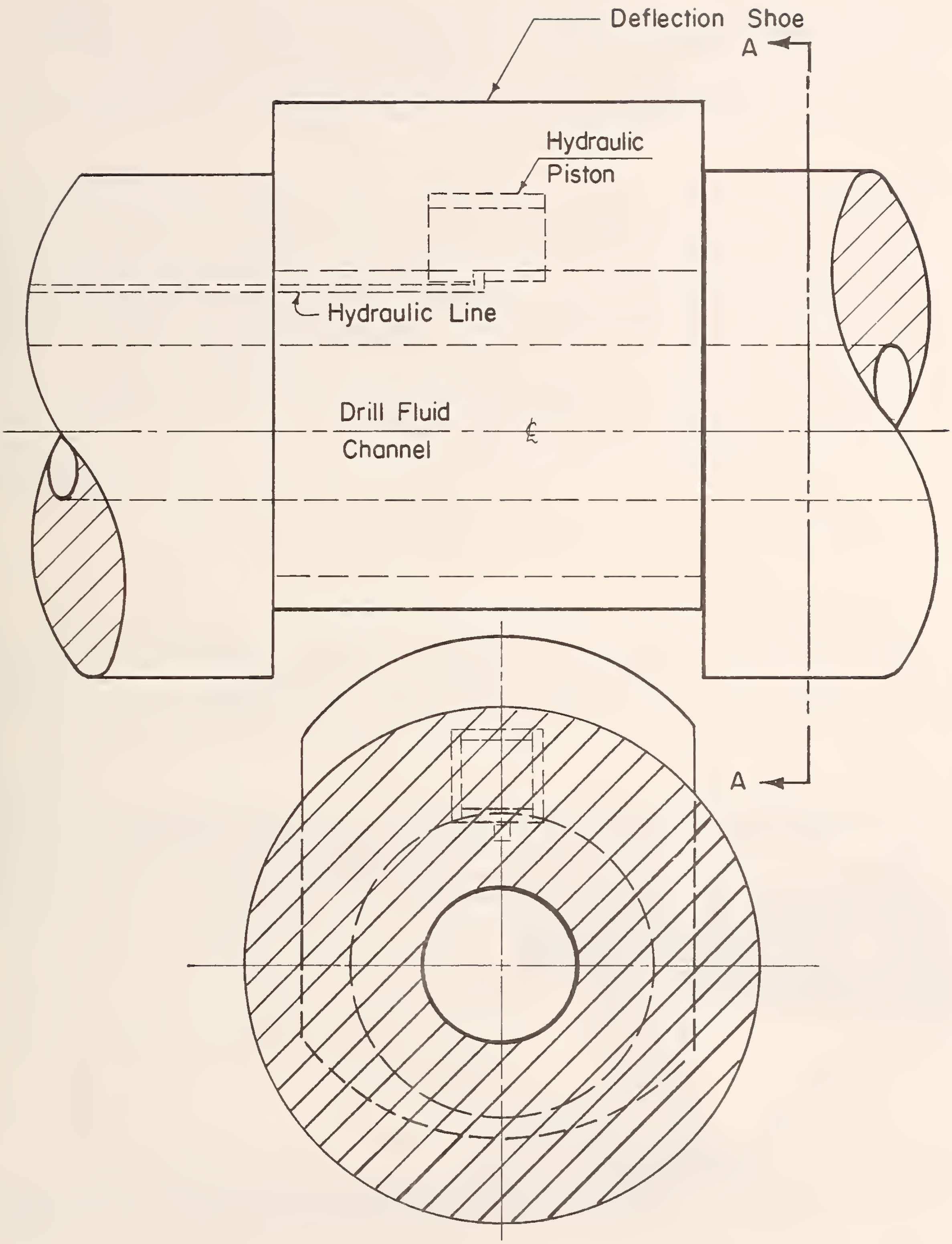


FIGURE D.12 SCHEMATIC OF CONOCO DEFLECTION SHOE
(After Edmond, 1975)

When the deflection shoe is not in use, it is flush with the adjacent drilling equipment and has a maximum extension of 3/8 in(0.95 cm). When the annular space dictates a greater extension, an extension pad can be attached. The axial length of the shoe is approximately 8 in(20.3 cm), while its total contact surface includes an arc of 90° over the bore hole wall.

BIT BOSS

The "Bit Boss" has been developed by DRILCO to provide continuous and positive directional control of the bit (Garrett and Rollins, 1964). This deflection device slides over the outside of the downhole motor and has anchor shoes oriented to one side. The anchor shoes are pressurized by the drilling fluid which enters the expanding shoes through a port from the interior of the drillpipe. Due to the pressure differential between the inside and outside of the drill collar after the pump is turned on, the anchor shoes expand out against the drill hole wall, thereby applying a lateral load close to the bit.

The "Bit Boss" was developed for vertical oil well drilling, however it has potential applications, after modification, in horizontal directional drilling (Kellner, 1974).

JET BIT DRILLING

Another deviation technique in relatively erodable formations is jet bit drilling. The jet bit, shown in Figure D.13, is a roller cone drill bit which has one of its fluid nozzles enlarged, with respect to the remaining nozzles. The enlarged nozzle is then oriented in the direction

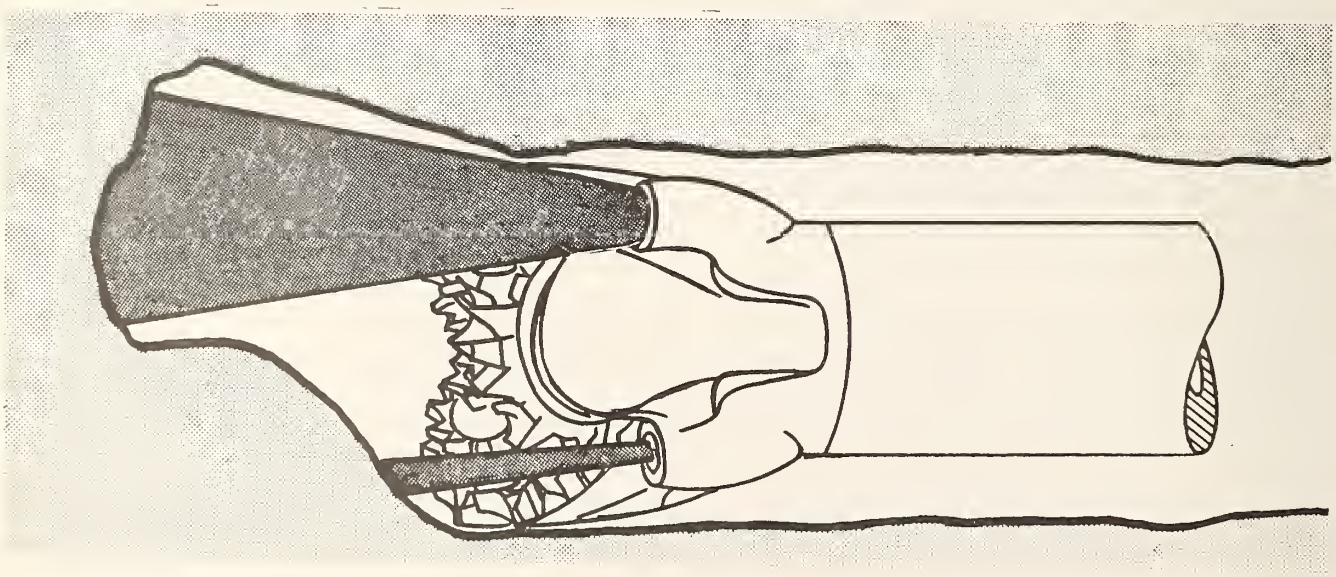


FIGURE D.13 JET BIT DRILLING
(After U. of Texas, 1974)

of the desired deviation. Without turning the drill string or bit, drilling fluid is pumped through the bit and the face is eroded asymetrically with the greatest erosion occurring nearest the enlarged nozzle. By increasing the normal force on the drill pipe, the pipe will bend in the direction of the washed out area since this is the path of least resistance.

Several problems are associated with jet bit drilling for horizontal, directionally controlled holes in soft ground. When the subsurface soil is silty or loose sand, jetting may wash out too large of a cavity thereby decreasing the controllability of the drill path. Most importantly, when the enlarged nozzle is directed up towards the ground surface, the overextended cavity reduces the underside soil resistance, thus resulting in the bit dropping down under the influence of gravity.

A major reason for the nonadaptability of jetting to horizontal directional drilling with downhole motors is the inability to lock the bit while pumping. Since the bit cannot be maintained in one position relative to the drill hole, the jet bit drilling technique is not compatible with a hydraulic downhole motor.

D.5 SOFT GROUND DRILLING BITS

Rotary drilling bits presently available for soft formation drilling are as numerous as the types of expected formations. The basic external geometry of the three main types of bits currently in use in soft ground drilling are illustrated in Figure D.14. Each basic bit has been developed for a specific type of drilling.

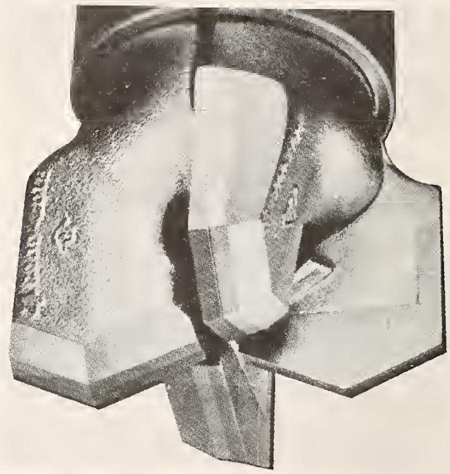
TRICONE BIT

The tricone roller bit has excellent sidetracking capabilities, because of the contact angle of the widely gapped, deeply cut heel teeth. Therefore, it is well suited for directional drilling. However, the teeth can become clogged. The service life of a tricone bit is not only a function of the wearability of the cutting teeth but also includes the wearability of the bearing assembly within each cone. Therefore, the tricone bit should not be operated at high rpm, usually not any more than 500 rpm. Because of the size of the journal bearings within each cone, tricone roller bits are not normally manufactured for less than 3-1/2 in (8.9 cm) O.D. holes.

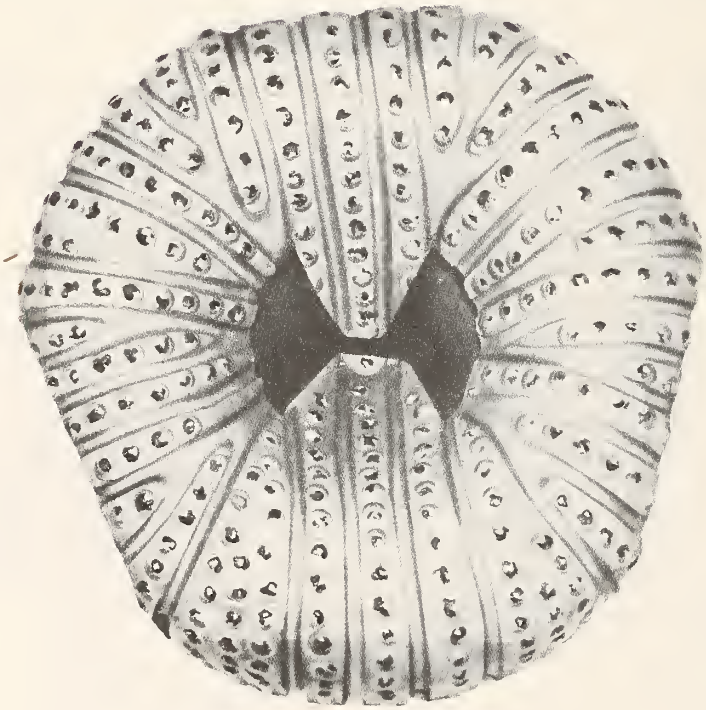
DRAG BIT

The drag bit is a good soft ground bit because its flat chisel shaped teeth are easily cleaned. Because of the flat plate cutting surface, the drag bit requires greater torque compared to the roller cone bit. The drag bit is the least expensive of the three types of bits and is available in sizes less than 3-1/2 in (8.9 cm) in diameter. The service life of these bits is solely a function of the cutting plate wear, therefore there is no established equipment limit on the operational rpm.

Tricone
Roller Bit



Drag Bit



Diamond Bit

FIGURE D.14 BASIC SOFT GROUND DRILL BITS

DIAMOND BIT

The diamond bit has a long service life, but is also the most expensive drilling bit among the three types. An advantage of a diamond bit for soft ground drilling in abrasive formations (occasional boulders) is the possible continuous use for the entire drill path. This possibility is, however, a function of the type of formation and the normal load. Another positive point for the diamond bit is that it can be used at high rpm (1000+) for long periods while maintaining good sidetracking ability. Presently, the diamond bit is usually produced for drill holes in excess of 5 in (12.7 cm), however small diameter bits can be ordered as special items.

In order to select the proper drill bit, one must consider normal load, speed of rotation, soil formation, necessary side cutting loads, duration time of drilling, and the lubricity of the drilling fluid (Allen, 1972).

There are several drill bit companies that make standard size bits as well as specially fabricated bits.

APPENDIX E

NAVIGATION AND COMMUNICATION EQUIPMENT FOR HORIZONTAL PENETRATION

E.1 INTRODUCTION

Navigation requirements for horizontal boreholes differ considerably from those for vertical holes. Not only are all of the tolerances more exacting, but the relative importance of azimuth accuracy to elevation accuracy is much greater for the horizontal problem. In consequence, much of the current borehole survey technology cannot be applied directly to this problem. Rather, new systems must be designed within the framework of unique performance and environment specifications.

Three targeting accuracies are proposed to provide a range of possible system configurations and several bases for economic impact evaluation. As a transportation tunnel normally is on the order of 20 ft (6 m) in diameter, the navigation system should be capable of identifying the position of the drill bit to within 10 ft (3 m) over the short course of 1000 ft (305 m). A more desirable goal, and one which is the general aim of the components specified in their appropriate sections, is 10 ft (3 m) in 5000 ft (1525 m). The most demanding tolerance anticipated would not call for less than 1 foot in 5000 ft (1525 m). In each of these specifications, equal emphasis is placed on azimuth and elevation uncertainties, unlike vertical borehole surveying where drift is much more important than heading. As a result, none of the existing instrumentation is capable of meeting the more stringent tolerances. Under ideal circumstances, where magnetic anomalies are extremely weak, magnetometers might provide sufficient accuracy to accommodate the lowest targeting accuracy specified, and some existing survey equipment might be adapted.

The approach to a total navigation system design depends very much upon whether or not a rotating drill string is employed. If it is, the drilling environment for the navigation instruments probably is significantly more severe than if a downhole motor is used to drive the drill bit. Furthermore, the rotating drill string requires a telemetering system to transmit navigation data, whereas a signal cable might otherwise be used, provided a system for fishing it through drill string sections could be devised. A slipring assembly, for accommodating a cable in a rotating drill string, would not be practical for mud-filled holes below the water table.

The acceleration and vibration environment of the drill is the least understood element of drilling technology. Practically no data have been published; the notable exception is the results of tests

conducted by Esso Production Research Company (Oil and Gas Journal, January 8, 1968) which recorded radial, axial, and angular accelerations of an instrumented rotating drill collar. Depths ranged from zero to 5700 ft (1738 m) and accelerations were as high as two g's, axial and radial. The drilled medium was not identified in the short record sample which indicated these acceleration levels. Presumably it was rock. The system addressed here is intended for drilling in unconsolidated materials most likely with a downhole drill motor. This drilling environment has not been measured. One can only speculate that the environment should be less severe than that encountered in the Esso tests.

The following sections describe the most common of the existing borehole survey equipment to provide a basis for comparing the needs of horizontal boring. Sections on discrete instruments needed to build a satisfactory system follow. Finally, a section describing telemetering systems either existing or under development completes the examination of the borehole navigation and communication system.

E.2 CURRENT BOREHOLE SURVEYING EQUIPMENT

The equipment available to drilling operations for surveying the direction of boreholes range from the very coarse to instruments capable of fairly good resolution, in terms of survey requirements. Inclination is universally measured by means of a pendulum (accelerometer). Azimuth is determined primarily with a magnetic compass; where imperfectly defined magnetic anomalies prohibit their use, gyros or gyrocompasses replace them.

Most of the equipment considered here is applied to near-vertical holes. The instruments are encased in narrow cylindrical canisters. They are periodically lowered on a wire or cable through the drill string to determine the borehole orientation. Trip times are on the order of two hours for a 20,000 ft (6100 m) well. No gyro units stay with the drill during the drilling operation. As a result, relatively low-grade gyros can be employed. They typically exhibit drift rates of four to six degrees per hour when operating satisfactorily.

Drift and heading are most commonly recorded on photographic film. Survey tools use either single shot or multiple shot camera systems which are activated by timers. An example is shown in Figure E.1. Exposure periods also can be initiated by sensors which recognize the termination of vibration, an indication the probe has been stopped along the drill string to take a measurement. After the survey, the probe is withdrawn from the well and the film is developed. The image resembles a bull's-eye with a spot representing the orientation of the borehole. The distance of the spot from the center of the film is a measure of drift, and its angular location from a radial line identifies the borehole heading. In some systems, notably the Humphrey Gyrosurveyor, the Scientific Drilling Controls EYE, and the Sperry Sun steering tools, the photographic recording is replaced by electronic sensors and data are transmitted through the suspension cable for

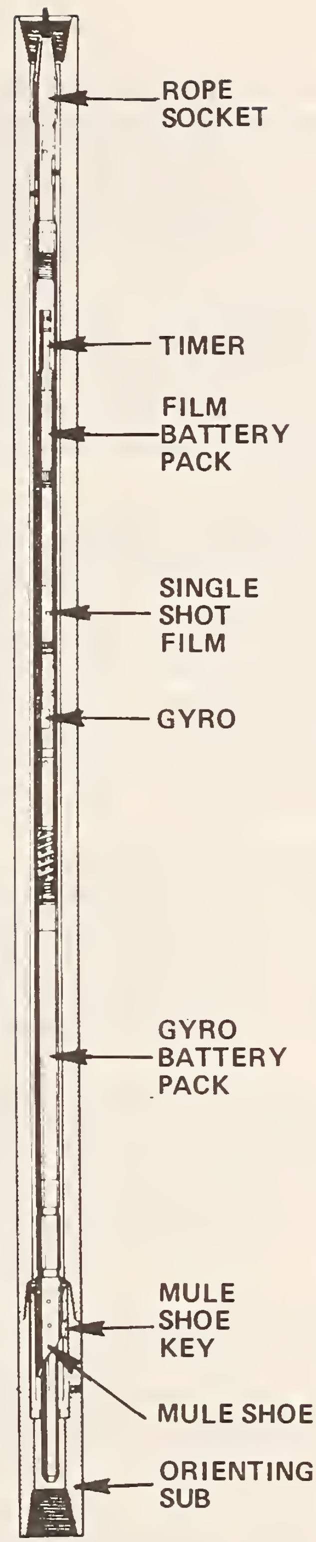


FIGURE E.1

DRILL COLLAR WITH SPERRY SUN SINGLE SHOT GYROSCOPE IN POSITION (After Sperry Sun)

continuous monitoring. The latter two systems are used specifically for steering the drill bit when a turn in the borehole is being developed. In this instance, the drill string is nonrotating, a mud-motor drill is employed, and only one or two drill sections are added. Thus the problem of feeding a continuous cable through discontinuous drill steel is avoided.

Table E.1 presents the physical and operational characteristics of most existing surveying tools. Drift angle measurement accuracy can be quite good, even with very simple instrumentation. Azimuth accuracy, however, necessarily suffers from either extreme miniaturization, or the basic limitations forced by magnetic field anomalies. For vertical holes, this is of little concern.

With the exception of the mechanical Dyna-Drill units, all would fit in small-diameter drill steel. Those with photo read-outs have self-contained battery power supplies. As all units (except the one model of the Humphrey Gyrosurveyor described) are intended for vertical holes, adaptation to horizontal use involves employing a greater inclination range, and consequently a reduced resolution. To maximize resolution for particular applications, manufacturers commonly offer a number of ranges for their instruments. Depth limitations almost without exception are more than adequate for the present application.

A variety of leasing schedules are possible; those illustrated are representative of the oil industry. Only Humphrey offers a gyro tool for outright purchase. The Sperry-Sun Surwel contract includes the furnishing of a field technician to operate and maintain the survey equipment. Service life figures represent unpublished estimates offered by technical personnel of the corresponding manufacturers.

In summary, none of the existing borehole survey equipment investigated is immediately applicable to the present horizontal boring problem. Either interfacing with telemetering equipment is impossible (required in the event that a rotating drill string is employed), or performance is inadequate for all drilling locations likely to be encountered in urban areas.

E.3 DISCRETE COMPONENTS

The main components of any navigation package, in their order of discussion, are accelerometers, magnetometers, and gyroscopes.

ACCELEROMETERS

The choice of an accelerometer to measure elevation angles for horizontal boreholes is predicated on many factors, the most important of which are null repeatability and shock and vibration survival. It is very fortunate that many models in a broad range of very low cost instruments can satisfy even the most rigid navigation requirements of this operation.

TABLE E.1 AVAILABLE NAVIGATION EQUIPMENT

NAME AND COMPANY	MECHANIZATION	DIMENSIONS	POWER REQ'TS	ANGLE LIMITS	DEPTH LIMIT	TEMP. LIMIT	PRESS. LIMIT	RESOLUTION AND ACCURACY	OUTPUTS ANO READOUT	CABLE REQ'TS	PURCHASE/ RENTAL COSTS	SERVICE LIFE
GYROSURVEYOR HUMPHREY (HORIZONTAL SURVEYOR)	DIRECTIONAL GYRO PENOULUM WITH POTENTIOMETER	1.38" OIA.	28V OC FROM 115V 60Hz SUPPLY	±60° INCL. ±45° AZIMUTH	1500 FT (1000 FT DIST. TO OATE)	250-300°F	15K PSI WITH 3/8" CASE	RES .1° INCL. ACC .1° INCL. GYRO ORIFT 4-6°/HR GOOD	DC VOLTAGES, SCANNED DIGITAL DISPLAY, PRINTOUT	4 COND.	PURCHASE $14K-$22K	400-5D0 HR GYRO BEARINGS
SURWEL SPERRY-SUN	GYROCOMPASS, PENOULUM	1-3/4" AND 3" OIA.	SELF-CONT. D CELLS 30V	0-2° TO D-9D° INCL. 360° AZIMUTH	23K FT	—	—	RES 5' INCL. ACC 6"/1000 FT GYRO DRIFT 1°-3°/HR GOOD	PHOTO-SINGLE SHOT	WIRE LINE	RENT SERV. 23¢/FT $92D MIN.	20 HRS IN HOLE
MAGNETIC MULTISHOT SPERRY-SUN	MAGNETIC COMPASS, PENOULUM	1-1/4" DIA. AND 1-3/4" D SHIELD	SELF-CONT. D CELLS 8-10V	0-2° TO 0-120° INCL. 360° AZIMUTH	—	600° FOR 5 HRS	—	RES 5' INCL. ACC.~1/2° BEST FOR AZIMUTH	PHOTO-MULTISHOT	WIRE LINE	RENT 12¢/FT $420 MIN.	700-800 HR IN HOLE
SINGLE SHOT SPERRY-SUN	MAGNETIC COMPASS, PENOULUM	<1-3/4" DIA.	SELF-CONT. D CELLS 8-10V	—	>20K FT	~400°F	—	—	PHOTO-SINGLE SHOT	WIRE LINE		—
EYE SCIENTIFIC DRILLING CONTROLS	3 AXIS MAGNETOMETERS 3 AXIS ACCELEROMETERS	<1-3/4" DIA.	OC VOLTAGE	0-90° INCL. 360° AZIMUTH	>16K FT	>300°F	2DK PSI.	RES .01° INCL. .01° AZIMUTH .01°/100' DOG LEG .01 FT	PRINTOUT INCL., AZ., DEPTHS (2) LATITUOE, E-W OEPART., DOG LEG SEV.	SINGLE CONO. (SHIELD GNO.)	RENT $980/8 HR ANO WIRE LINE $280+4¢/FT	100 HR
TELEDRIFT OYNA-ORILL	PENOULUM ACOUSTIC PULSE OUTPUT	5" DIA.	NONE	10-1/2° INCL. 3-1/2° RANGE	>22K FT	—	—	RES 1/2°	ACOUSTIC PULSES: 1 PER 1/2° IN.	NONE	—	—
TELEORIENTER OYNA-ORILL	ROTATING COUNTERWEIGHT ACOUSTIC PULSE OUTPUT	5" DIA.	NONE	360° AZIMUTH	>22K FT	—	—	RES 20 TO 90°	ACOUSTIC PULSES: TOOL BIT WRT LO SIOE	NONE	—	—
GYROSCOPIC MULTISHOT EASTMAN	DIRECTIONAL GYRO PENOULUM	3-1/8" DIA.	SELF-CONT. O CELLS 31V	0-12° TO 0-70° INCL. 360° AZIMUTH	12K-26K FT	300°F FOR 3 HRS	—	RES 1/4° INCL. (INTERP. TO 5') GYRO ORIFT <6°/HR	PHOTO	WIRE LINE	RENT SERV. 22¢/FT $895 MIN.	~3 MO MTB REPAIR

1 in. = 2.54 cm
1 ft. = 0.305 m

$^{\circ}F = \left(\frac{F - 32}{1.8}\right)^{\circ}C$

(1 psi = 6.90 kN/m^2)

While a complex mission error analysis could be conducted, it is more meaningful to investigate the consequences of one source of error; namely, the null shift, to provide insight to the limitations of navigation instrumentation. The accelerometer will be oriented in the drill collar so that nominally no output occurs when the collar is horizontal. Null offset and misalignment of the true instrument sensitive axis from the collar axis lead to a nonzero reading when the drill collar is level. The net result could be an inclined borehole equal to this offset value, which is reflected in an exit position error ahead of or behind the target (Δx). The geometry is illustrated in Figure E.2 for a downward sloping bore.

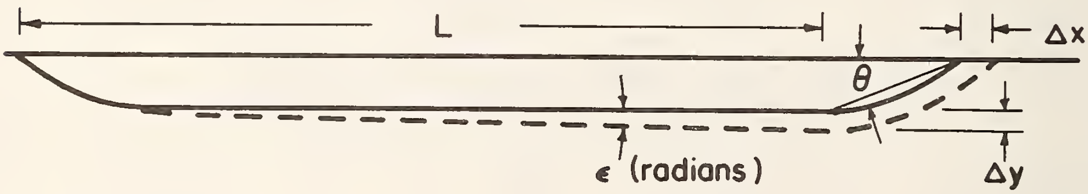


FIGURE E.2: Geometry of Downward Sloping Borehole When Accelerometer Misaligned and Subjected to Null Shift

With the assumption of a constant drill angle, ε , over the bore distance L, the following relations are developed readily.

$$\Delta y = L\varepsilon$$

$$\Delta x = \Delta y \cot \theta$$

$$\frac{\Delta x}{L} = \varepsilon \cot \theta \quad < \varepsilon \text{ for } \theta > 45^{\circ}$$

If the exit error is to be small, the exit angle, θ , must be large, or the drift must be overly constrained. As a practical example, forty-five degrees is assumed, and the percentage target error is equal to the drift. Target errors relate to drift as follows:

Target Error	Drift
10 ft @ 1000 ft (305 m)	.01 rad or .6 deg.
10 ft @ 5000 ft (1525 m)	.002 rad or 6.7 arcmin
1 ft @ 5000 ft (1525 m)	.0002 rad or .67 arcmin

The drift can be related directly to the null error. As this is normally related to the full-scale range of the accelerometer, choice of an instrument with a small range is desirable. For example, an accelerometer having a null error of .05% and a range of $\pm$.5g would yield a borehole drift of .00025 radian for this one source of error. This nearly falls within the most stringent requirements proposed in the table above, if the exit angle is sufficiently large. This example illustrates how systematic instrument error leads to navigation error. Calibration is proposed below to eliminate most of this.

The mode of operating the accelerometer in a horizontal borehole permits the selection of very low cost units. By operating within a very limited range near null along most of the borehole, nonlinearity, scale factor, and hysteresis errors are negligible. Output noise can be averaged to eliminate this error source. Other errors include resolution, nonrepeatability, null offset, and temperature coefficient of null. Of these, null offset is the largest, but can be known to the level of instrument resolution. When an accelerometer is mounted within a drill collar, four nonvarying errors accumulate to produce an output signal when the collar is level. The sensitive axis of the instrument is aligned with the case to within a prescribed tolerance. The mounting surface in the collar will not be parallel to the collar axis. Nonlinearities and electronics biases will produce an output signal even if the true sensitive axis is level. Cross-coupling error accompanies these and is constant since the cross axis acceleration always is one g. The sum of these errors can be calibrated and compensated during operation.

The error sources which remain to degrade navigation performance are time varying, perhaps with frequencies sufficiently low to prohibit averaging. Non-repeatability is the largest of these, but is likely to be less than the quoted specification because of the limited operating range. Both resolution and temperature coefficient of the null are much smaller than non-repeatability, provided some effort is made to control temperature to a few degrees.

Table E.2 gives the pertinent performance and operating parameters specified by several manufacturers of low cost accelerometers. Figure E.3 shows the accelerometer dimensions. From the foregoing discussion of error sources, the choice of instrument for even the most stringent borehole navigation requirements is open to several models described in the list.

Before making a final choice, aspects of the drilling environment must be considered. No definitive vibration spectrum has been measured for the particular drilling operation considered here. It is known, however, that the Dyna-Drill causes some vibration, presumably at its rotation frequency of about 20-60 Hz. Since rock will be penetrated only infrequently, the most severe vibration levels associated with this type of drilling will be avoided. However, if the instrument canister is vibrated to an amplitude of only 0.007 inch (0.02 cm) at 60 Hz, the peak acceleration would be 10 g's. Some isolation may

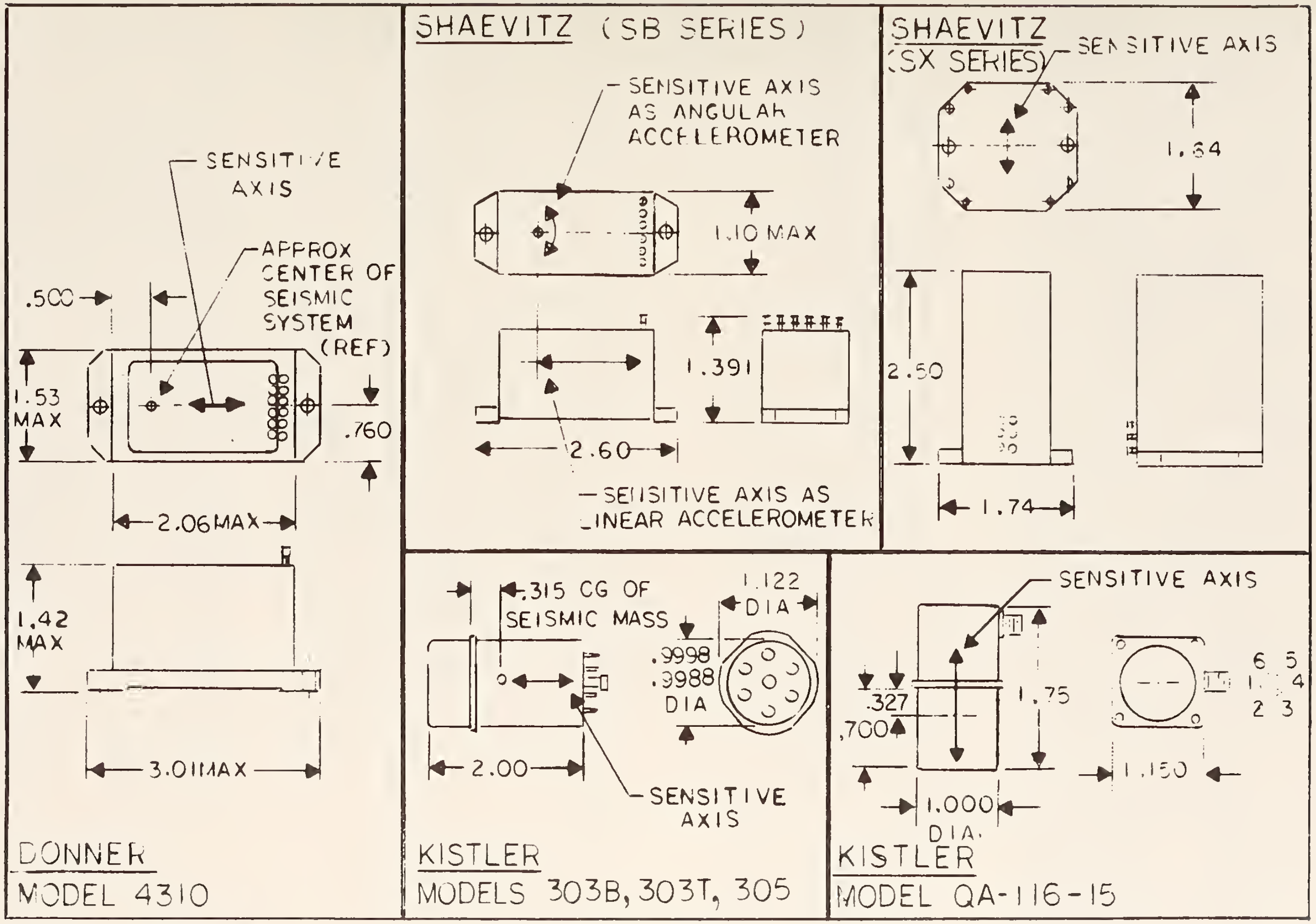
TABLE E.2 ACCELEROMETER SPECIFICATIONS

Mfgr., Model, Cost	Donner 4310 ~$450	Donner 4311 ~$625	Schaevitz LSxV ~$450	Schaevitz LSC ~$385	Kistler 303 ~$450- to $750	Kistler QA-116-15 Q-Flex ~$400 - to $650
Accuracy Parameters						
Nonlinearity	<.05% F.R.	<.015% F.R.	.05% F.R.	.05% F.R.	.05% F.R.	.03% of reading
Hysteresis	<.02% F.R.	<.01% F.R.	.0001% F.R.	.02% F.R.	.0005 g or .1% F.R.	.001% F.R.
Resolution	<.001% F.R.	<.001% F.R.	.0001% F.R.	.0005% F.R.	.00001g	10^{-6} g
Nonrepeatability	<.01% F.R.	<.01% F.R.	-	-	.1% F.R.	.003% F.R.
Null Offset	<.05% F.R.	<.05% F.R.	<.1% F.R.	<.1% F.R.	<.05g	<.02g
Null Temp Coeff	<.001% F.R./°F	<.001% F.R./°F	-	-	.03g/100°F	.0002g/°F
Output Noise	<.05% F.R.	<.05% F.R.	5mv	5mv	5mv max, DC-1Hz	1mv RMS
Crosscoupling	<.002 g/g	<.002 g/g	.002 g/g	.002 g/g	.002g/g	.002g/g
Scale Factor Temp Coefficient	<.01%/°F	<.005%/°F	.015%/°F	.01%/°F	.02%/°F	.01%/°F
Environmental Parameters						
Temp Range Storage	-65 to + 200°F	-65 to + 200°F	-65 to +220°F	-65 to + 220°F	-	-
Operation	-40 to +200°F	-40 to + 200°F	-40 to +200°F	-40 to + 200°F	-65 to +185°F	-65 to + 200°F
Shock Survival	100g, 11ms	100g, 11ms	100g, 11ms	100g, 11ms	100g, 5ms	250g, 11ms
Vibration Survival	15g RMS 20-2KHz	15g RMS, 20-2KHz	5g RMS, 20-2KHz	10g, 20-2KHz	±20g, 5 to 2KHz	50g peak, random sine
Physical Parameters						
Range	±.5g to ±35g	±.5g to ±50g	±.25g, ±.5g, ±1g	±.25g to ±50g	±.5g to ±50g	±15g
Output Voltage	±7.5 or ±15 vdc	±7.5 or ±15 vdc	±5 vdc	±5 vdc	±5 vdc	250 mv/g
Input Power	±15 vdc @ ±10ma or ±28 vdc @ 15ma	±15 vdc @ ±10ma or ±28vdc at ±15ma	±15 vdc @ 10ma	±15vdc @ 10ma	28 vdc @ 40ma	±15 or ±28vdc
Case Alignment	+1° to TSA	+1° to TSA	-	-	-	-
Weight	<7oz, Fluid damping	<2oz, F. D.	7.5oz.	3oz.	3.3oz.	2.6oz.

F.R. = Full Range

TSA = True Sensitive Axis

$$°F = \left(\frac{F - 32}{1.8}\right)°C$$



1 in. = 2.5 cm

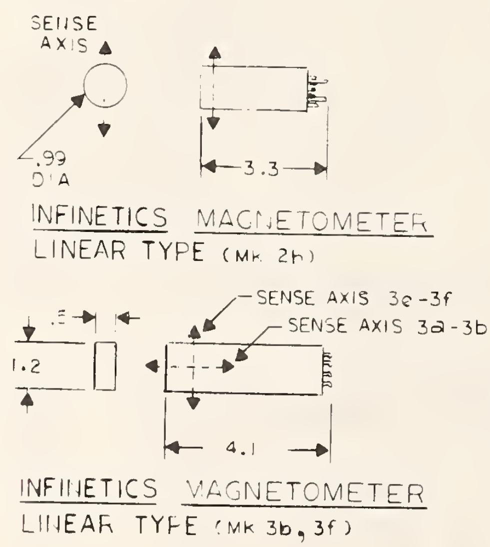
FIGURE E.3
ACCELEROMETER DIMENSIONS (IN)

be required in order for the instruments to survive. If satisfactory alignment of the accelerometer sensitive axis with the drill collar is to be maintained, it is preferable to shock mount the entire instrument canister rather than individual accelerometers.

MAGNETOMETERS (MAGNETIC NORTH-SEEKING DEVICES)

The principal limitation of using north-seeking instruments to establish an azimuth reference rests with the uncertainties in the sensed field. Noise levels of magnetometers normally reflect about two to three minutes of arc orientation error. Field disturbances can range to more than two orders of magnitude greater than this level. They are the result of unknown underground magnetic masses in the vicinity of the borehole, currents in electrical cables, magnetic materials in the drill bit and collar, and thunderstorm activity or even unsettled weather conditions.

Thus, for urban tunnelling navigation, magnetometers are not proposed as a primary azimuth reference. However, because there may be the possibility of developing a hybrid reference system by combining their data with that from a gyro, their characteristics are considered in some detail. An excellent, inexpensive fluxgate magnetometer (shown in Figure E.4) is manufactured by Infinetics, Inc., and operates on the



1 in. = 2.5 cm

FIGURE E.4
MAGNETOMETER DIMENSIONS (IN)

second-harmonic principle. The Infinetics device incorporates oscillator, filter, and demodulator electronics in the magnetometer housing, so that only regulated direct current is applied and the output is a dc voltage proportional to the field component along the sensitive axis.

For the magnetometers, linearity, noise, and other errors are sufficiently small to permit resolving the orientation of the earth's field to better than one-half degree by using an orthogonal triad of sensors. With careful effort, one-tenth degree might be realized. However, field uncertainties would prohibit the attainment of such resolution for borehole azimuth. Perhaps the best use of magnetometers since they exhibit excellent stability and a noise level of two or three arc-minutes, would be in conjunction with a gyro, wherein periodic stopped-drill measurements would determine the drift rate of the gyro and a filtering technique would be employed while drilling to combine the two types of sensor outputs to determine borehole azimuth.

GYROSCOPES (GYROS)

In those environments where magnetic anomalies prevent the use of magnetometers, or for missions which demand greater accuracy than is possible with these instruments, gyros offer the only alternative to measuring the azimuth of the borehole with on-board instrumentation. There are several ways to employ gyros to obtain a bearing measurement, but, in essence, only one is meaningful under the prescribed navigation accuracy.

Current borehole survey tools including gyros, with the exception of the Sperry Sun Surwel, employ the simplest mode possible. The gyro is free to maintain its spin axis orientation with respect to inertial space. By gimballing, it is independent of the motion or position of the drill collar. The disadvantages of this technique are that earth's motion remains uncompensated and any friction in the gimbal bearings develops torques which precess the gyro and create azimuth indication errors. Current survey tools are restricted to short operation times; they are pumped downhole, a reading is taken, and they are withdrawn. The low accuracy required for vertical holes permits a linear interpolation of the accumulated drift angle from the start of the drop to the finish of the retrieval to generate a drift correction.

For on-board navigation of horizontal boreholes, this simple use of gyros is inadequate. Heading accuracy requirements are much more demanding, and call for use of a gyro in a manner similar to that common to inertial navigation systems found in aircraft. The gyro is rigidly mounted in the drill collar and measures the component of the earth's angular velocity along its input axis. In the case of a two-degree-of-freedom gyro, two components are measured. By knowing the elevation angle and roll orientation of the drill collar, obtained from accelerometer measurements, the azimuth angle can be identified from these earth rate component measurements. If the input axis is aligned with the drill collar axis, the earth rate components are given by:

$$\omega = \omega_{ie} (\cos\lambda \cos E \cos A + \sin\lambda \sin E)$$

where ω_{ie} is the earth's angular velocity (15 deg/hour), λ is latitude, E is elevation angle, measured from the horizontal, and A is the heading measured from north. This technique works well so long as the heading is not close to north or south, where cos A has little change with heading. To overcome this problem and permit unrestricted drilling direction, two gyro axes would be used, one along the collar axis and one normal to it. If a downhole motor drives the drill bit, and the instrument collar can maintain a roll orientation within a few degrees, only two gyro axes are required. If this is not the case, three are required, as heading is determined only from the component of earth's angular velocity lying in the horizontal plane. If two-degree-of-freedom gyros are substituted, only two are needed to cover all azimuths and roll orientations. Furthermore, if a special indexing fixture is devised to rotate a 2 DOF gyro about one axis, as depicted in Figure E.5, only one gyro is required to measure drill heading for any orientation. Thus, a considerable cost savings can be realized from this scheme. Additional comparative comments on single- and two-degree-of-freedom gyros are included below.

To choose a gyro for the horizontal boring program would require a full system study. The greatest unknown is the acceleration and shock environment of the instrumentation collar, and final choice would be predicated on satisfactory knowledge of this environment. However, the basic performance requirements can be specified independently and consequently the class of gyro needed for this job can be identified. If the equation above is rewritten in terms of parameter uncertainties, it becomes,

$$\delta A = \frac{\delta\omega}{\omega_{ie} \cos\lambda \sin A \cos E} + \frac{\delta\lambda}{\sin A} - \frac{\delta E}{\tan A}$$

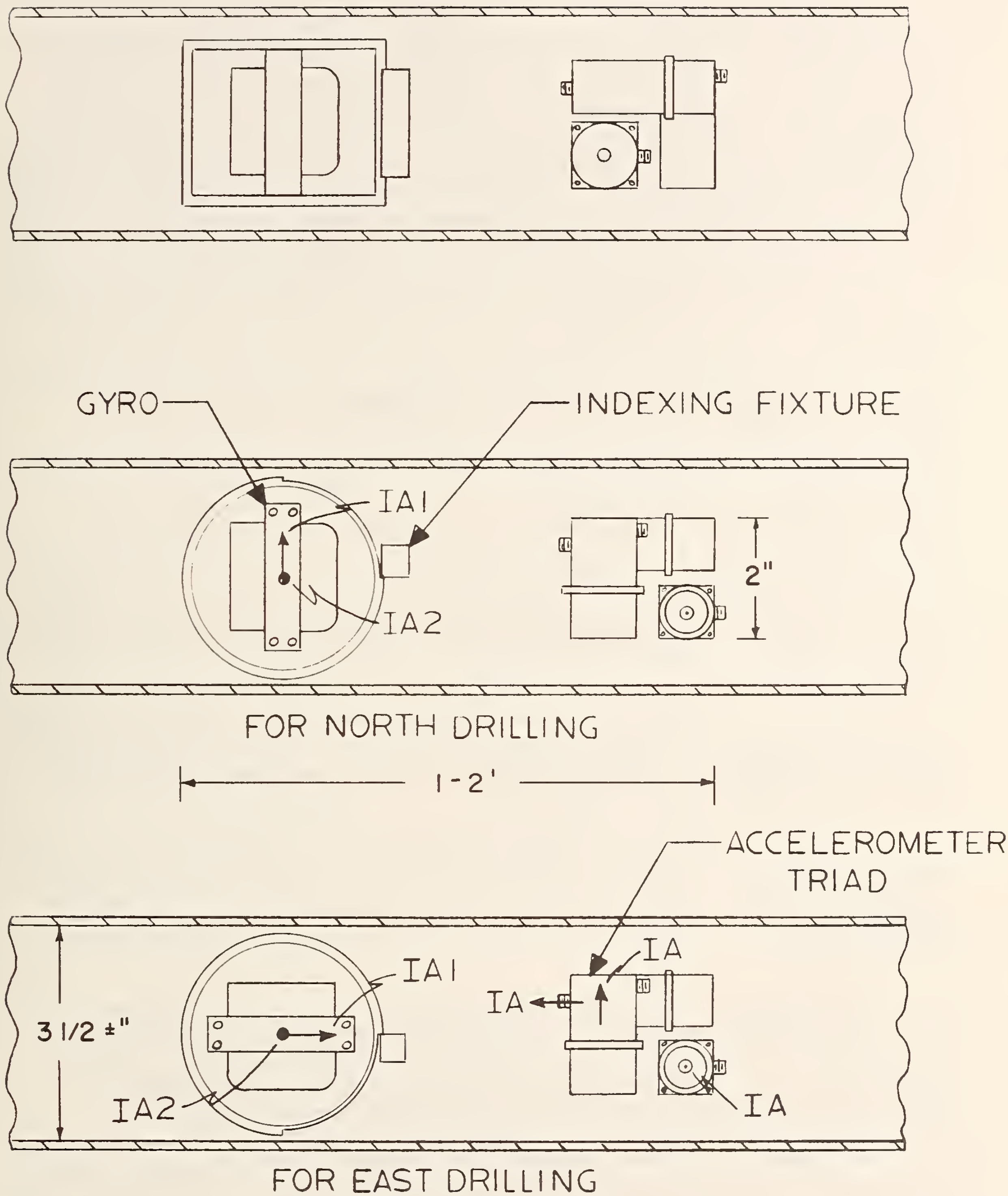
To obtain a numerical example, latitude is assumed to be 45 degrees, and azimuth is greater than 20 degrees.

$$\delta A = .3\,\delta\omega + 3\,(\delta\lambda - \delta E)$$

where $\delta\omega$ is the gyro drift rate in degrees per hour.

In the accelerometer section, targeting errors were translated into inclination errors. The same values can be applied to azimuth with little error. For the intermediate accuracy level, the requirement is .002 rad. This would call for a gyro with a drift rate uncertainty less than .0067 deg/hr. The least demanding heading accuracy of .01 rad requires a gyro drift within .034 deg/hr.

The choice of azimuth of twenty degrees influences these drift requirements rather strongly. If instead, 45 degrees is chosen, the drift can be twice as great. However, shifting from a one-gyro axis configuration (axis along drill collar) to the two-axis configuration, as heading approaches north, would introduce some small uncertainties resulting from the additional computational complexity and alignment uncertainties. The optimum crossover point is closer to north than 45 degrees. These numbers serve to estimate the class of gyro required.



1 in. = 2.5 cm
1 ft = .304 m

FIGURE E.5

INSTRUMENTATION CANISTER

(For nonrotating drill collars)

Examples above consider only constant drift rates to simplify the concept of gyro-related azimuth errors. In practice, the non-statistical drift characteristics of gyros are well-modeled and would be compensated. The random drift characteristics are the real error contributors. Relating these to azimuth errors is very complex and includes the consideration of operation time, shock and vibration environment, and gyro orientation with respect to gravity. That is beyond the scope of this report; identifying instruments which probably would perform adequately and are of a reasonable size to not overly constrain the packaging problem is possible from the simple analysis above.

Two generic classes of gyros dominate the aircraft inertial platform field. The single-degree-of-freedom (SDOF) floated integrating gyro was first to be developed. It has excellent shock and vibration survivability owing to the floated design. It is relatively expensive on a unit basis, but has provided the highest accuracies for missile guidance systems. Three gyros are required for a complete system. The two-degree-of-freedom (2 DOF) flex-hinged gyro is a newer development. Over the past decade it has offered viable competition to the SDOF gyro in many applications. It is considerably cheaper than comparable SDOF models, in addition to providing an additional input axis which results in only two instruments for a complete system and offers some redundancy. There is some sacrifice of shock and vibration survivability, but the temperature sensitivity is much lower than for the SDOF gyro. These gyros also are quite small, which is an important factor in the drilling system.

Because of the cost and size considerations, gyro selection would center on the 2 DOF models. Two manufacturers offer good candidates, Kearfott and Litton. Table E.3 lists the most important characteristics of the 2 DOF gyros.

Although the environment specifications and the electronics costs are not available for the G-1200, they would be comparable to those for the Gyroflex. These instruments are very small for their performance. They consistently demonstrate accuracies better than those listed above.

The maximum torquing rate may present some handling problems. Even the Kearfott unit with a rate limit of about two degrees per second would demand care when moving the instrument canister outside the borehole. <u>A reasonable precaution would be to run up the gyro wheel only after the canister is at least partway downhole</u>.

The indexing fixture suggested in Figure E.5 illustrates a method to minimize instrument expenditures while not restricting drilling azimuths. For drilling within, say 45 degrees of east, one input axis should be aligned with the drill collar axis. Closer to north, both axes should be normal to this axis so that a relatively large angle is maintained between north and the gyro input axes. This scheme can be mechanized by a simple, fixed-stop indexing housing at some sacrifice

of minimum gyro package size. If the instrument collar does not rotate about its axis beyond a few degrees, the fixture is not required.

While a variety of gyro configurations is possible, including a gyrocompass which self-aligns to east, considerable expense would be involved in their development. Such systems may not be warranted in view of the availability of the gyros described above. Had only larger gyros been available, the development might have been a requirement. In summary, existing two-degree-of-freedom gyros, having very small size and excellent performance, should be applicable to the horizontal boring navigation problem. By suitable mechanical design only one gyro is needed to identify azimuth, thus minimizing instrument costs.

TABLE E.3: SPECIFICATIONS FOR CANDIDATE 2 DOF GYROS

	Litton G-1200	Kearfott Gyroflex
Dimensions (In.)	1.65" LOA, 2.13" Flange	1.7" LOA 2.13" Diameter
Torquer		
Scale factor stability (PPM)	100 PPM	100 PPM
Maximum rate (^{o}/hr)	900^o/hr	7000^o/hr
Performance		
Random drift (deg/hr)	.005 deg/hr	.002 deg/hr
g-sensitivity (deg/hr-g)	.01 deg/hr-g	.005 deg/hr-g
Temperature sensitivity (deg/hr-^{o}F)	.003 deg/hr-^{o}F	.006 deg/hr-^{o}F
Environment		
Shock (g)	--	30 g's, 11 msec 150 g's, 1 msec
Vibration (g)	--	10 g's, 10-2K Hz
Cost		
Unit ($K)	$10K-$12K	$10K-$12K
Electronics ($K)	--	$3K

(1 in. = 2.54 cm)

$$1\ ^oF = \left(\frac{F - 32}{1.8}\right)^oC$$

E.4 COMMUNICATION CONCEPTS

Developing communication system technologies differ principally in the frequency and type of wave employed to transmit data. Four telemetry systems are discussed below and shown in Table E.4. Telcom's system operates with a 4050 Hz electromagnetic carrier frequency which propagates principally through the drill string. Raytheon's system operates with a 20 Hz electromagnetic frequency which propagates both through the ground and the drill string. Teleco's system operates with acoustic pulses which propogate principally through the drilling fluid. Weston's system operates by locating the source of the 20 Hz seismic pulses, which propogate through the ground.

TELCOM, INC., CABLELESS DRILL-GUIDANCE SYSTEMS

A technique for telemetering sensor data from a drill bit to the surface of a borehole has been developed by Telcom, Inc., of McLean, Virginia, under the auspices of the U. S. Bureau of Mines. A program to develop the equipment was initiated about three years ago. Two systems were built, one each for horizontal and vertical holes. While the expected operating range of the systems was 7500 ft (2288 m), the longest demonstrated to date has been about 1400ft (427 m) by the vertical system.

The telemetry system sequentially accepts dc voltages from an accelerometer and a three-axis magnetometer and converts them to digital information. A schematic of this conversion is shown in Figure E.6. The data are organized behind a preamble message which prepares the receiver for the transmitted information. The data are used to modulate a carrier frequency of 4050 Hz by a phase shifting technique. Positive phase shifts indicate ones, and negative shifts denote zeros (Figure E.7). The entire data block consists of about 128 bits and takes less than ten seconds to be transmitted. The transmission rate is approximately 15 bits/sec with no drilling. Transmission is triggered by a pressure switch which senses a pulse in the drilling fluid, controllable by the drilling operator.

The telemetry transmitter is a coil which induces a current in the drill string. The receiver employs a second coil at the head of the drill string to sense this current and to send the data to the processing center located in a truck near the drilling site (shown in Figure E.8). Here, the signal is decoded and a minicomputer (shown in Figure E.9) generates navigation information from the accelerometer and magnetometer outputs. The computed parameters include corrected bearing, true inclination, and their deviations from preset values. The borehole depth is entered manually and displayed with these parameters.

The lack of a standard down-hole survey package which could be interfaced with the telemetry system required the development of such a tool in order to demonstrate the feasibility of the telemetering

TABLE E.4 CHARACTERISTICS OF ADVANCED BIT COMMUNICATION SYSTEMS

NAME & COMPANY	MECHANIZATION	CARRIER FREQUENCY	DIAM O.D. (in)	LENGTH (ft)	POWER	ACTUATION	BITS/SEC	LENGTH TESTED	INVEST TO DATE ($1000's)	RESTRICTIONS
CABLELESS TELEMETRY TELCOM	Electrical Current through Drill String	4050	3	6	Battery	Mud Pulse	15.0	1,500	200 (from U.S. government)	1)Fluid Around 2)Up Hole Direction Only 3)Signals Only When Stopped
EXTRA LOW FREQUENCY RAYTHEON	Electro-Magnetic Waves through Ground	20-25	6	20	Battery (100 Watts)	Surface Signal	0.2*	11,000 (Surface Down)	300 (Company Funds)	1)2000Ft Diam Antenna 2)Fluid Through 3)Repeators Every 6000 Ft. 4)12 in Diam Cased Hole*
TELECO RAYMOND PRECISION	Pressure Pulse through Drill Fluid	N.A.	7-3/4	34±	Down Hole Turbine	Mud Pulse	0.07	11,000	3,600 (Company Funds)	1)12 in. Diam Hole
CABLE NUMEROUS	Signal through Cable	N.A.	ANY	ANY	Through Cable	N.A.	ANY	N.A.	N.A.	1)Operate by Wire Line Or Employ Down Hole Thruster

* Without Casing Data Rate Increases to 10 BITS/SEC.

1 in. = 2.5 cm
1 ft = .304 m

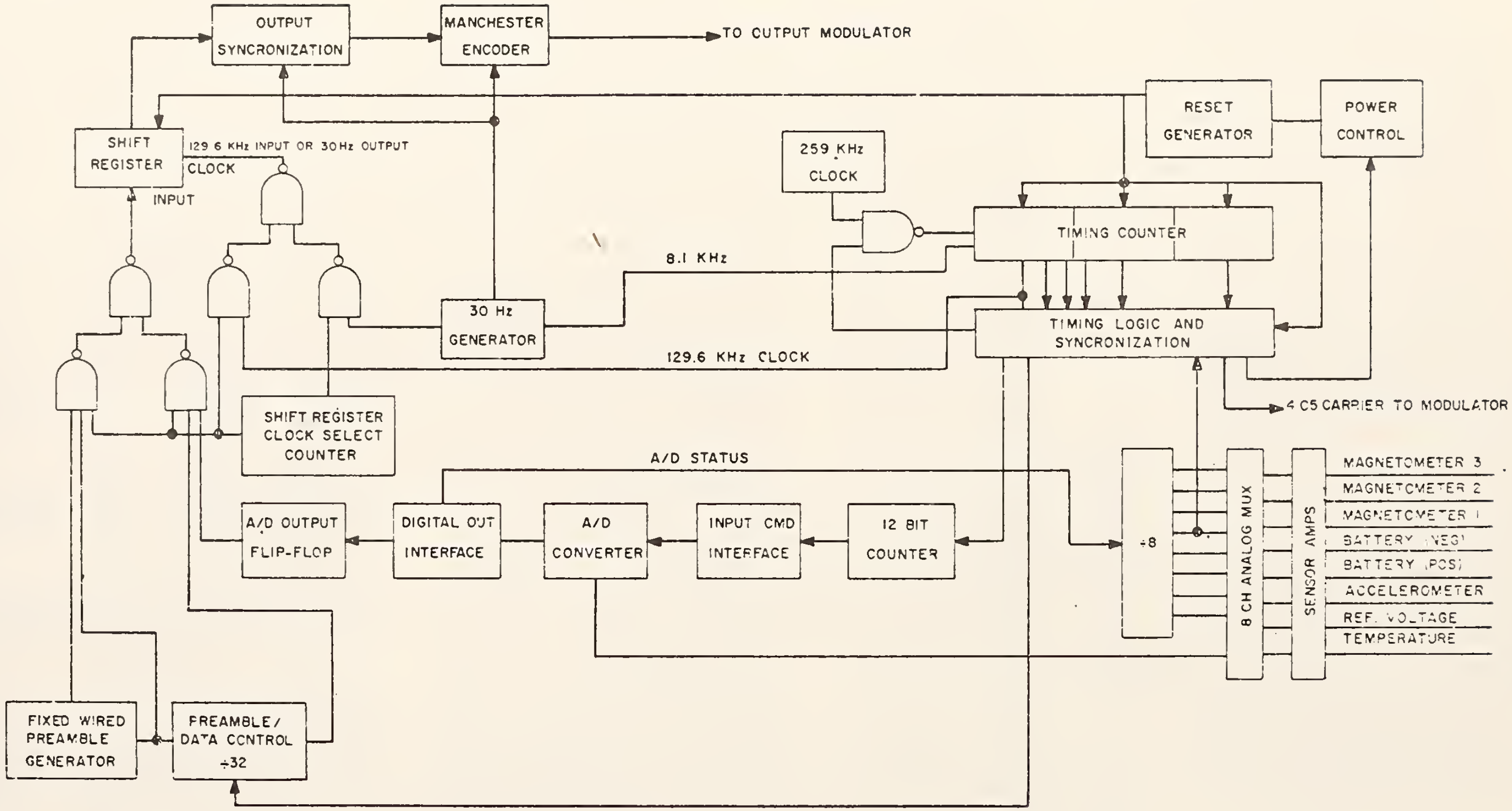


FIGURE E.6

LOGIC DIAGRAM - DOWN HOLE DATA UNIT

(After Telcom, 1975)

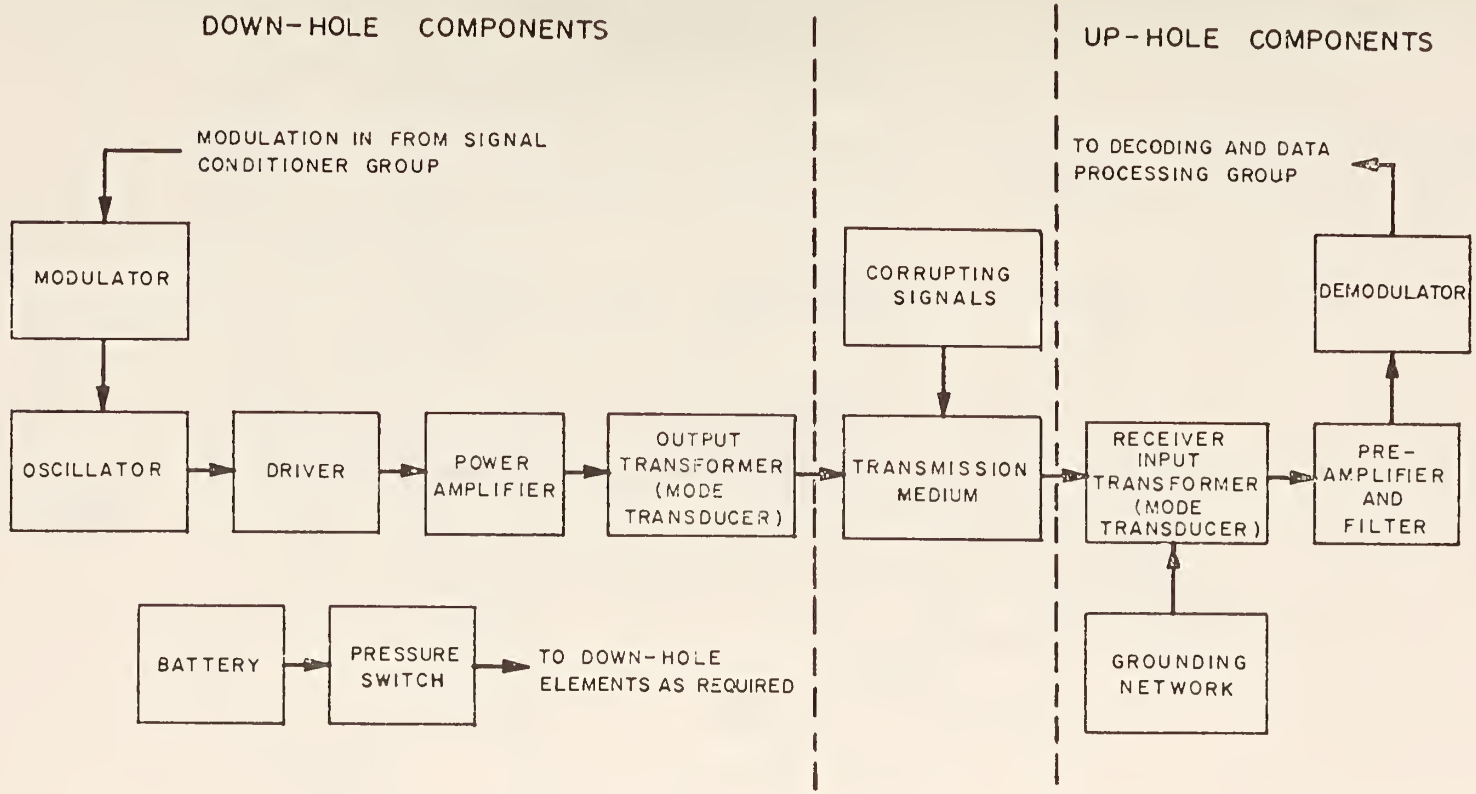


FIGURE E.7

BLOCK DIAGRAM-"CABLELESS" TELEMETRY SUBSYSTEM

(After Telcom, 1975)

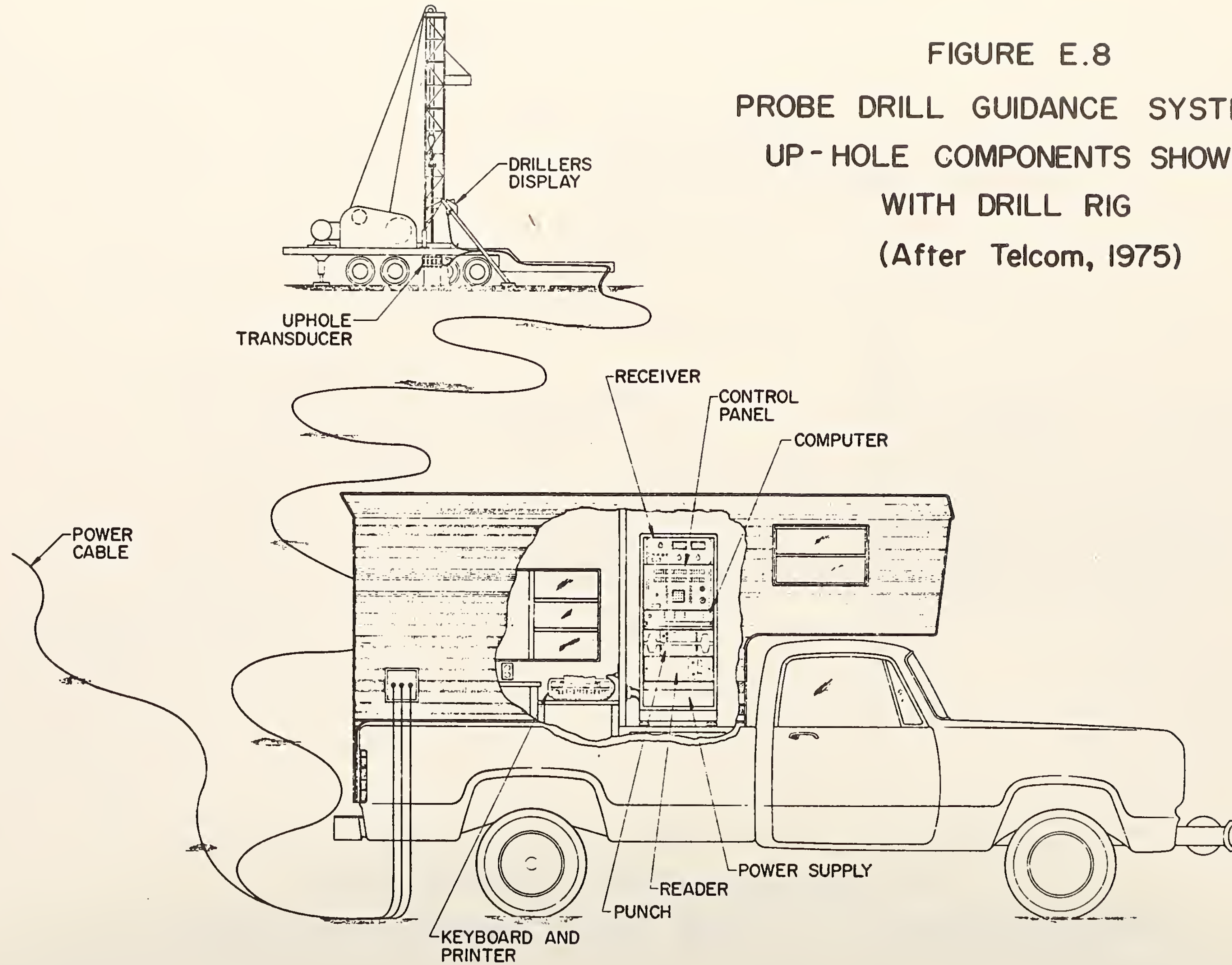
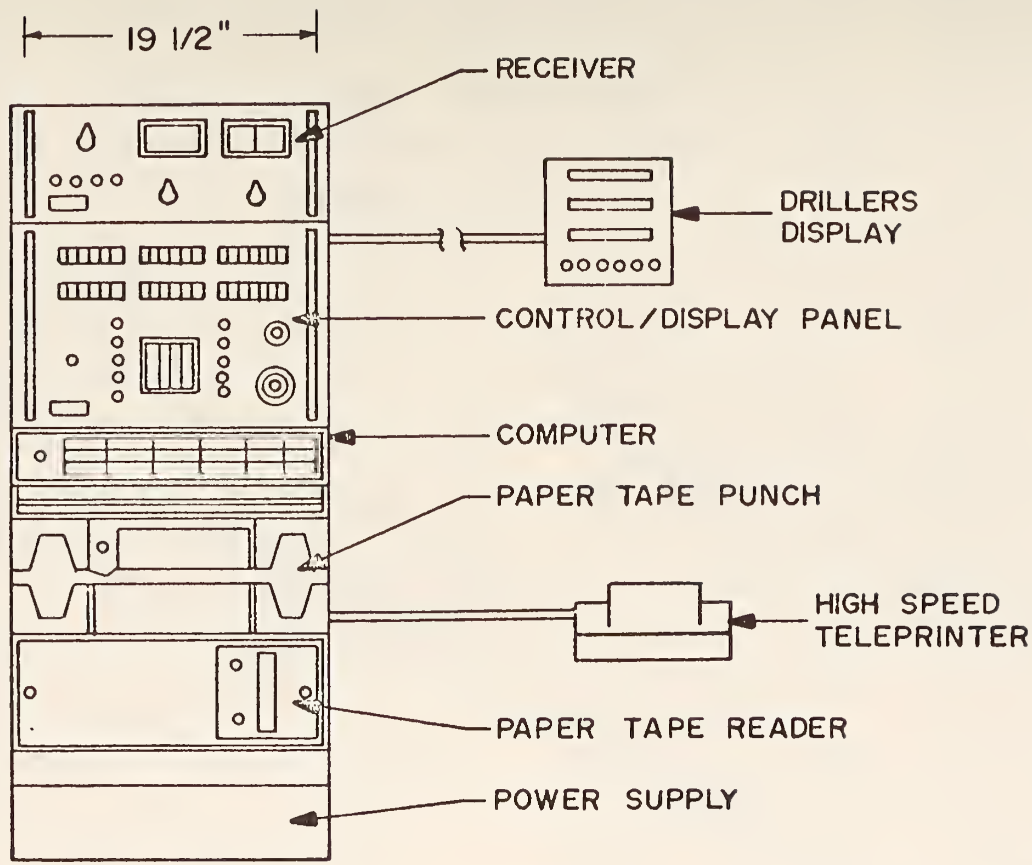


FIGURE E.8
PROBE DRILL GUIDANCE SYSTEM
UP-HOLE COMPONENTS SHOWN
WITH DRILL RIG
(After Telcom, 1975)



1 in. = 2.5 cm

FIGURE E.9

UPHOLE UNIT CONFIGURATION

(After Telcom, 1975)

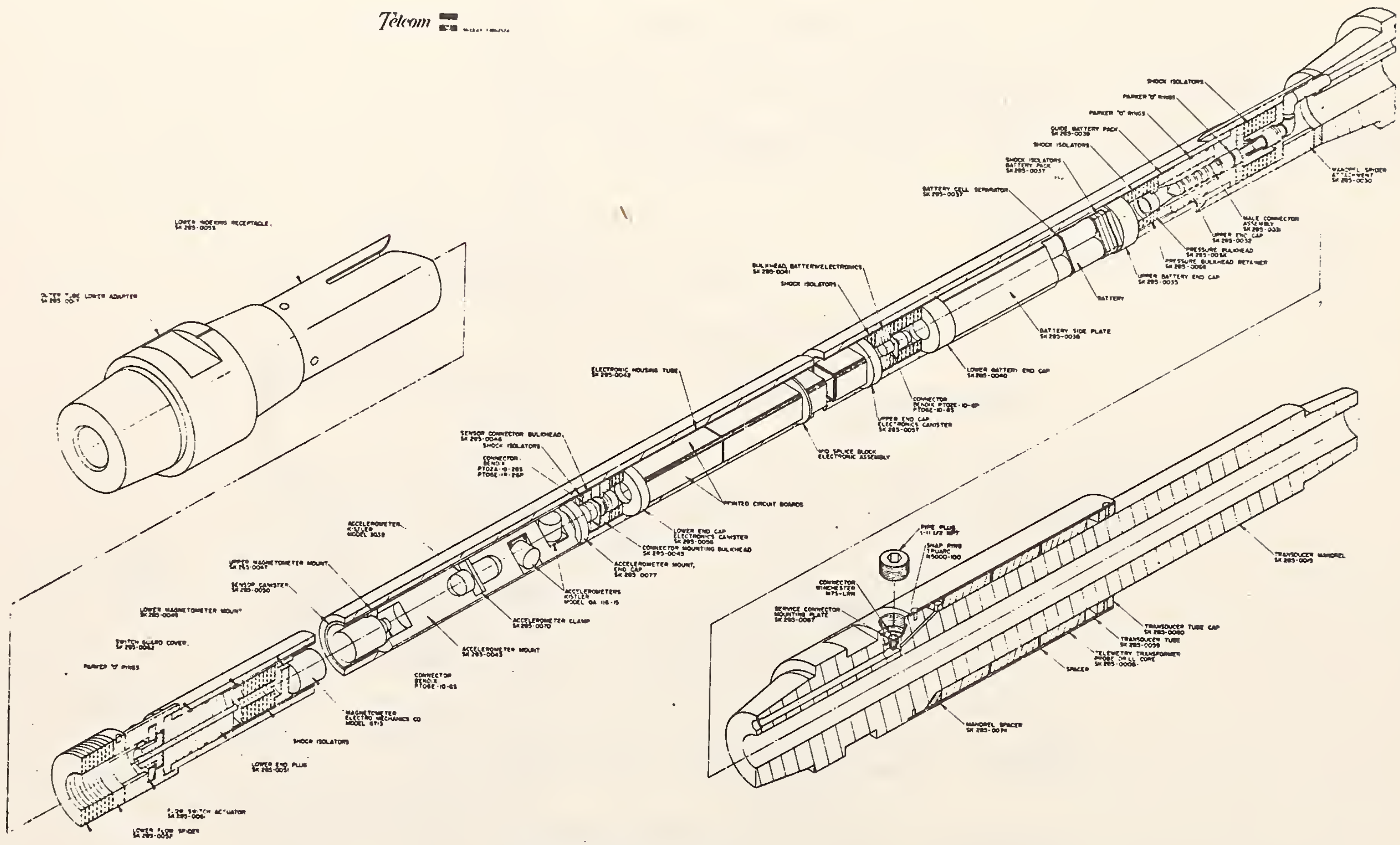


FIGURE E. 10

TYPICAL DOWN - HOLE SURVEY TOOL

(After Telcom, 1975)

concept. The result, for the vertical boring system, is shown in Figure E.10. The horizontal system needs just one accelerometer, and because of its smaller outside diameter (2 13/16 in. vs. 5 in.) has the electronics circuit cards and batteries spread over a greater length. The accelerometer is a Kistler Q-Flex, model QA-116-14, and the magnetometer is an Electromechanics Company Number 6713.

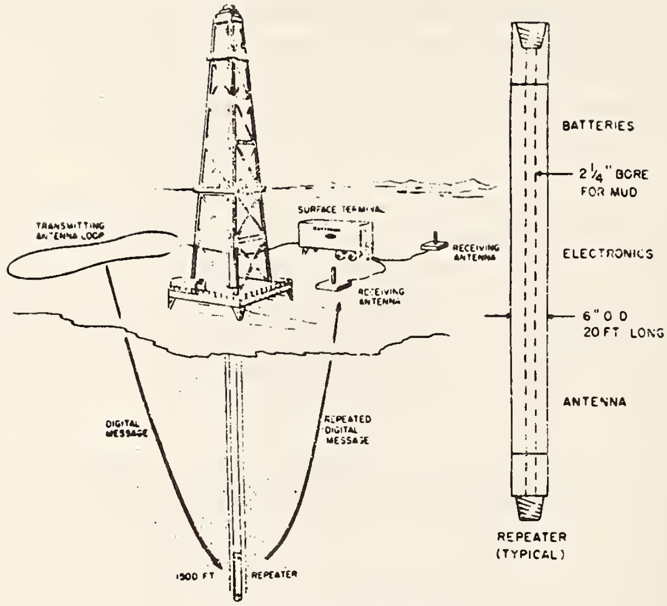
Although the Telcom systems have been in existence for over three years, they have not been in continuous operation nor further developed in that duration. Cost overruns resulted in litigation against the company which only recently was settled. Whereas the Bureau of Mines wanted fully operable survey systems, Telcom was embarking upon the development of a hitherto untried telemetering concept. In the net, the systems did perform, albeit sporadically.

The future of the Telcom system is not clear at the present time, and the company is not aggressively marketing the systems. The Bureau of Mines has invested approximately $200,000 for two drill guidance systems and responses from the contracting officers in charge of the projects are similar: the system did work, but did not reach the anticipated level of consistent operation. When compared with the company-funded levels by Raytheon and Teleco for similar systems, one is led to think too large a program was undertaken for the funding provided. It is beyond the scope of this report to examine the basis of this comment in great detail; the current status of the program and equipment are the strongest indicators.

RAYTHEON ELF BOREHOLE TELEMETRY SYSTEM

The Raytheon Company, Equipment Division of Sudbury, Massachusetts, has been developing an extra low frequency (25 Hz) electromagnetic telemetry system for linking sensors near the drill bit with the surface. About $300,000 of company funds have been invested in the development of this system. Two years ago the feasibility of transmitting control commands from the surface down to the drill bit was demonstrated using a transmission loop antenna several thousand feet in diameter. Successful communication to 11,000 ft (3355 m) was demonstrated. The current effort involves the packaging of electronics, batteries and a solenoidal antenna in a drill collar for upwards communication from the drill bit.

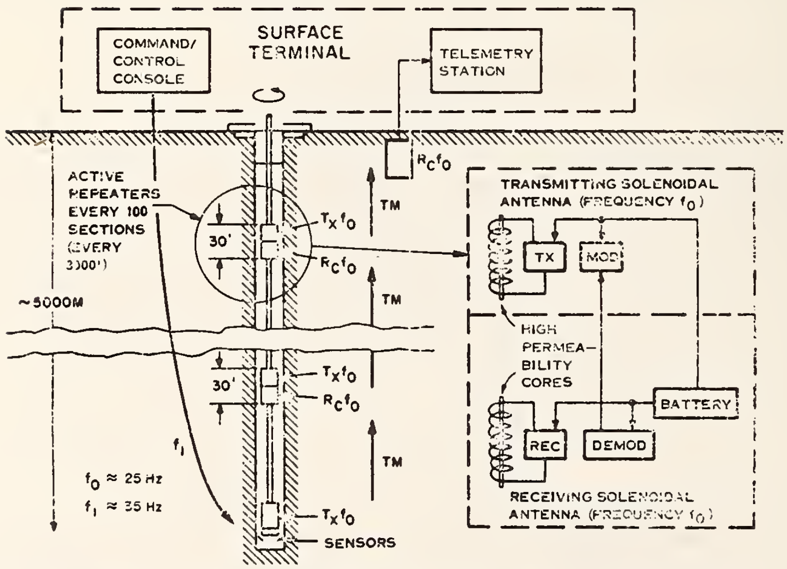
Transmission distance depends upon the conductivity and magnetic permeability of the earth, and the frequency of the propagated waves. Analytic investigations indicate the possibility of transmitting a 20 Hz signal over one kilometer if the lithospheric conductivity does not exceed 0.1 mho/m. Higher conductivity would limit transmission to shorter distances. The required transmitter power is about 100 watts. For deeper wells, a system of repeaters would be used to relay data to the surface. A pictorial view of this concept is shown in Figure E.11A. The repeaters would be contained in an annulus in a drill collar, thereby permitting unimpeded pumping of mud through a central bore. A schematic of these repeaters and their locations in the drill string is shown in Figure E.11B.



PROPOSED SYSTEM CONCEPT

(A) GENERAL CONCEPT

1 in. = 2.5 cm
1 ft = .304 m



(B) PRIMARY LINK REPEATER LOCATIONS AND CONFIGURATIONS

FIGURE E.11
RAYTHEON ELF BOREHOLE TELEMETRY SYSTEM
(After Raytheon, 1975)

In addition to the parameters cited above, an optimum design depends upon the levels of several types of noise, the most important of which are atmospheric, motion-induced, and man-made noise. Because of low attenuation of frequencies in the band of interest, atmospheric noise can be significant even for thunderstorms several thousand miles distant. By careful antenna design, which discriminates against the predominant horizontal magnetic field of this noise source, satisfactory reduction of this interference should be possible. Motion-induced noise is excited by the vibration of the transmitter antenna by the reaction of the drill bit. Because of the severity of this source, data will be transmitted only when the drill string is stopped for the addition of sections. An exception to this mode will be the continuous transmission of pressure data as a safeguard against blowout. Because of the drilling noise, the recovered data rate would be an order of magnitude less than that for the normal mode. Man-made noise sources include generators, motors and power lines. Surface antenna design techniques, including multiple arrays, can be employed to minimize these interferences.

The design objectives for the system are given below.

1.	Signaling Method	TDM-Multiple Hop Link
2.	Signal Frequency	24 Hz
3.	Maximum Temperature	175°C (347°F)
4.	Maximum Depth	20,000 to 35,000 ft
5.	Data Rate (Design Objective)	Drilling--1 bit/sec (Red Flag) Non-drilling--10 bit/sec
6.	Hop Length (Nominal)	3000 ft
7.	Mean Time Between Failures (270 Operational Days/Year)	2 years
8.	Canister Length	20 to 30 ft
9.	Canister Outer Diameter	6" (Typical)

The data are time-domain-multiplexed via a 24 Hz carrier. The six-inch canister diameter is appropriate to offshore drilling; smaller packaging to 4½ inches might be possible while maintaining a 2¼ inch mud bore. A list of potential parameters to be monitored is presented below as Table E.5.

A patent application for the telemetry system was filed in July, 1974, and a feasibility experiment is scheduled for September, 1975, in an oil well near Houston, Texas. To date, extensive system analyses have been completed and the canister and ground support equipment have been fabricated. The receiver and ground antenna have been designed. Assuming successful feasibility tests, Raytheon projects the availability of operational units in the latter part of 1976. Leasing likely would be conducted through a Raytheon subsidiary, Birdwell Division of Seismograph Service Corporation.

TABLE E.5: DRILLING DATA DESIRED AT WELL BOTTOM

1. "Red Flag" Information on Impending Blowout (Drill String in Full Rotation)
2. Drill String Directionality (Azimuth and Inclination)
3. Pressure
4. Temperature
5. Weight on Bit
6. Torque
7. Mud Resistivity
8. Bit Bearing Condition
9. Acceleration
10. Logging Parameters (With Bottom Package in Logging Mode)

TELECO SYSTEM

In 1972 Raymond Precision Industries, Inc., formed the Teleco subsidiary as a joint venture with a major French oil company (SNPA) to develop a drill string telemetering system operating on the acoustic mud-pulse principle. Up to the present time Raymond has made a $1.665 million cash investment in the development program and Teleco currently is operating on a second stage of financing of $2 million obtained as a five-year bank loan. Tests of the system have been made to more than 11,000 ft (3355 m). Present efforts are being directed to strengthen components to better withstand the drilling environment. The system is aimed at offshore oil exploration where the standard drill bit size is 12¼ in. (31 cm). If development progresses on schedule, the system will become available in the third quarter of this year. Projected leasing costs, based on a limited market survey, are anticipated to be in excess of $1000 per day.

Acoustic pulses are transmitted through the drill string mud by throttling the normally continuous flow through the drill bit by means of a control valve. The concept does not require drill stoppage; pulses are sufficiently strong to distinguish from normal drill chatter. Measurements of temperature and pressure have been demonstrated. Measuring borehole drift and heading does require drill stoppage, of course, as the sensor package is integral with the bit and drill string.

Sensor readings are transmitted in the form of four-digit words. Each digit is represented by one of ten frequencies, depending upon its value. One word takes approximately sixty seconds to be transmitted. At the surface, a pressure transducer receives the data which are subsequently decoded, displayed sequentially, and printed. Drill string depth is obtained manually from the drill operator.

Power for the sensor and transmitter package is developed by a mud turbine in the drill string. The complete system is housed in a 7-3/4 in (19.7 cm) O.D. by 34 ft (10.4 m) drill collar.

WESTON GEOPHYSICAL ENGINEERS, INC. SEISMIC POSITION DETECTION

A seismic navigation approach developed by Weston Geophysical Engineers, Inc., independently from this work, can provide an independent, continuous monitoring of position and elevation. The seismic nagivation approach utilizes L-shaped arrays of detectors on the ground surface or preferably a combination of ground surface arrays and borehole arrays to determine the direction and location of the origin of seismic waves.

It is anticipated that some exploratory drill holes, approximately 500- to 1000-ft (150- to 300-m) interval spacing, would be drilled prior to horizontal penetration. Thus, this approach includes both in-hole and on-surface arrays. Between the drill holes, the system provides a check on the penetrator's position. In highly urbanized areas, background noise can affect the reliability of such a system, especially with regard to the surface detector arrays. Therefore, for highly urbanized areas, only borehole arrays may yield satisfactory precision. These boreholes may also have to be closely spaced to provide the requisite precision.

In a quiet background environment, such as in water-covered areas or remote areas, the drill bit of the horizontal penetrator might be adequate as an energy source for detection. An additional energy source could also be included in the lead section of the horizontal device, such as an air gun or other explosive-like signal generator.

The seismic energy recorded across the various arrays would be processed immediately for continuous observation and determination of the position of the device. Accordingly, magnetic tape and/or photographic processing would be required. To further expedite this under-way position evaluation, the operator of the horizontal boring device could have time-distance nomographic presentations for position determinations. Such nomographs would permit the device operator to make an immediate decision concerning up, down, left, or right position adjustments.

The accuracy of such a seismic navigation system is dependent on a number of factors, but is generally anticipated to have a position accuracy of ± 10 ft (3 m) from the actual position. This anticipated accuracy assumes that a uniform velocity value, 5000 ft (1525 m)/sec for saturated overburden, will be the actual value along the line of the boring. This velocity value combined with an observational accuracy of ± 1 to 2 milliseconds will result in differences of ± 5 or 10 ft (1.5 m or 3 m) from actual position. Irrespective of this predictive capability and since the the seismic system is a continuously operational one, a reiterative procedure is anticipated; that is, predicted positions can be checked against actual positions as the horizontal device passes a borehole and corrections made for data obtained between observational drill holes.

Three limitations that must be considered for proper utilization of this navigation system are: (1) variations in overburden velocity from the assumed value of 5000 ft (1525 m)/sec, (2) refraction of an underlying high velocity layer that is relatively close to the boring device energy source, and (3) attenuation of the source signal which may preclude deep operation.

Since this system is relatively simple and can utilize on-shelf equipment, it is anticipated that substantial system development costs would not be incurred and the only applicable cost would be the daily operational charges of the organization performing the position determinations. Also, the length of an operating day for the horizontal boring device is dependent on a number of logistical and operating cost conditions; therefore, a typical service company's daily rate has been normalized to an hourly basis for estimating purposes. That resultant anticipated charge is approximately $100 per hour; a charge which is inclusive of operating expenses, data reduction, and a report on predicted, corrected, and final position data.

E.5 UPHOLE DISPLAY AND CONTROL UNIT

The incorporation of many technological innovations in the horizontal boring system calls for control and display equipment quite uncommon to present drill rigs. Not only are special power supplies and electronics required to run the various subsystems in the drill, but sensor output displays and processors also are required. Since this information is important to the drill operator, controls for the downhole motor hydraulics and the cone piezometer would be conveniently located in this unit.

The navigation sensor data must be transformed into drill bit position and orientation coordinates. The calculations, while normally feasible by hand, could be handled more efficiently by a small computer. A large number of instrument calibration parameters must be used to obtain the required navigation accuracy. Drill string or cable length would remain a manual input to keep track of borehole length.

Additional computer requirements may be generated if the sparker is included in the drill. Seismic data must be processed to determine soil characteristics. Alternatively, hydraulic controls are required to extend and retract the cone piezometer.

A reasonable example of the volume the display and control unit will occupy is the Telcom system. It is housed in a truck with a camper top and consists of one full height standard electronics rack, plus a teletype printer. The rest of the space is used as work, storage, or heating and air conditioning areas. This total space probably will be compatible with the requirements of the present system concepts.

APPENDIX F

DRILLING FLUID AND HORIZONTAL PENETRATION

F.1 INTRODUCTION

To drill horizontally with a downhole fluid powered motor, the drilling fluid must:

(1) Power the motor, (2) Clean and cool drillbit and bearings, (3) Remove cuttings from the drill face and carry them out of the borehole, (4) Suspend cuttings in-hole when fluid circulation is stopped, (5) Release the cuttings in the surface fluid cleaning system, (6) Protect the drilled formations from damage by penetrating fluid (filter cake), (7) Ensure hole stability by preventing caving of the borehole, (8) Possess rheological properties which preclude hydraulic fracture of the formation.

Filter caking and stability, (6) and (7), will be discussed under Stability of Horizontal Boreholes (Appendix H). Circulation requirements for cooling and power, (1) and (2), were introduced in Excavation Equipment for Maneuverable Horizontal Penetration (Appendix E), and only the energy losses associated with the fluid circulation will be discussed here. Item (5) will be treated in terms of the required recirculation system.

The fluid's cuttings transport potential and the associated potential for hydraulic fracture--(3), (4), and (8)--are hydraulically related but have opposite requirements. A viscous fluid is needed to suspend the cuttings during transport, yet these high viscosities require high circulation pressures at the bit which will hydraulically fracture the soil. Therefore the hydraulic design of the penetration system requires optimization of the viscous and fracture characteristics for each type of formation to be drilled.

One hydraulic optimization with four possible penetration systems will be presented in this appendix. The results lead to an optimum hydraulic system and the process delineates the effects of the drilling fluid on horizontal penetration in varying geologies. These four systems were selected to give a broad range of hole sizes and fluid flow rates. Details are given in Table F.1.

With these four candidate systems in mind, the effects of the drilling fluid will be discussed in the following order: (1) Rheology of Bentonite Slurry, (2) Annular Bit Pressure (ECD), (3) Cuttings Transport, (4) Total Circulation Pressure Losses, (5) Hydraulic Fracture, (6) Cable Friction, (7) Filter Cake Erosion, and (8) Fluid Recirculation Methods.

TABLE F.1: FOUR EXAMPLE SYSTEMS FOR HYDRAULIC OPTIMIZATION

Number	System Motor	Motor Diam. in. (mm)	Cable/Pipe Diam. in. (mm)	Hole Diam. in. (mm)	Fluid Flow Rate gal/min (dm^3/min)
1	2 3/8 in. Dyna-Drill	2.38 (60.3)	2.38 (73.0)	4.5 (114)	32 (122)
2	4 1/2 in. Electric	4.50 (114.4)	2.0 (50.8)	7 (178)	30 (114)
3	5 in. Dyna-Drill	5.0 (127.0)	2.0 (50.2)	7 (178)	225 (855)
4	6 3/4 in. Dyna-Drill	6.75 (171.5)	6.62 (168.3)	12 (305)	350 (1330)

F.2 RHEOLOGY OF BENTONITE SLURRY

A Bentonite Slurry behaves as a Bingham plastic fluid which enables the slurry to transport cuttings more effectively than water, a Newtonian fluid. Properties of these two fluids are compared in Figure F.1a. The bentonite slurry has abnormally high shearing resistance (τ) at low strain rates ($\dot{\gamma}$) compared to water. This shear resistance (or strength) at low strain rates enables cuttings transport through decreased settlement rates. However, the higher shear strength also requires greater fluid pressures than water to maintain equivalent flow rates. If the strain rate drops to zero (no flow) the slurry gains strength ("sits up," "gels") through thixotropy. This thixotropic strength is helpful in hole stabilization, but as shown in Figure F.1b requires abnormally high pressures to begin (break) circulation.

The initial portion of τ-$\dot{\gamma}$ plot for an idealized slurry (A-D) can be idealized as

$$\log\tau = \log K + n \log (\dot{\gamma})$$

where K is the τ intercept at $\dot{\gamma}$ = 1 and "n" is the slope of the straight line when Figure F.1a is plotted in log form as in Figure F.2. The log-log plot of this relationship can be thought of as a stress-strain diagram for the mud slurry. Log K is the dynamic yield point of the mud slurry and the "n" value is the dynamic viscosity of the fluid.

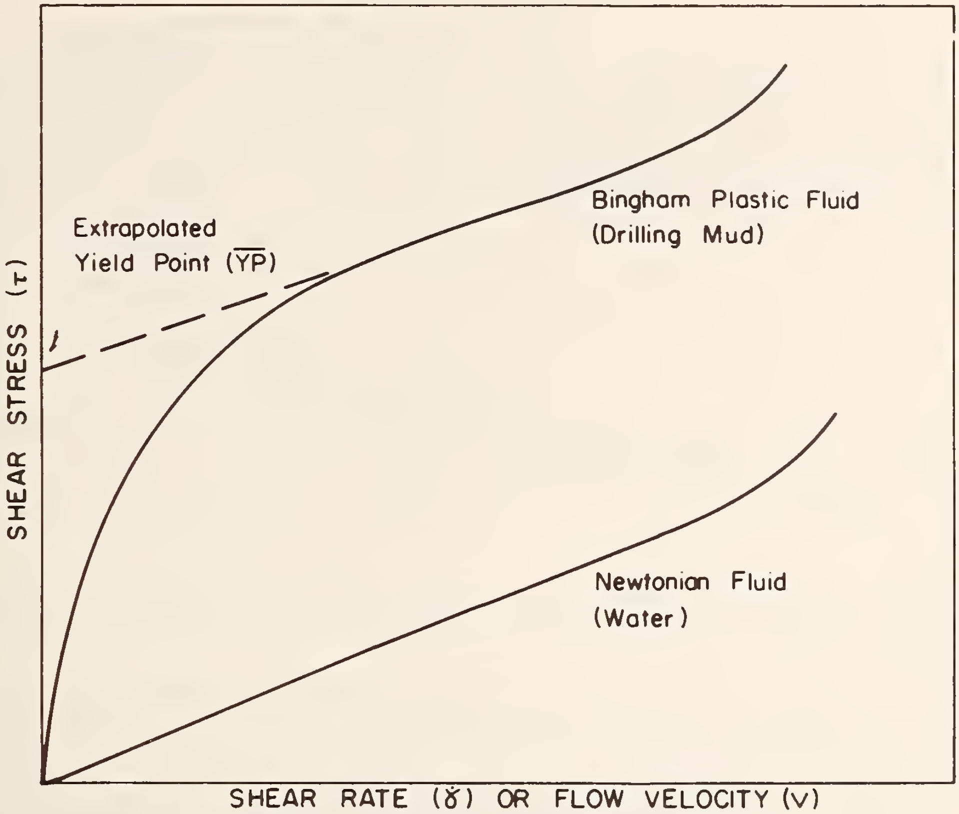


FIGURE F.1a RHEOLOGY OF BINGHAM PLASTIC

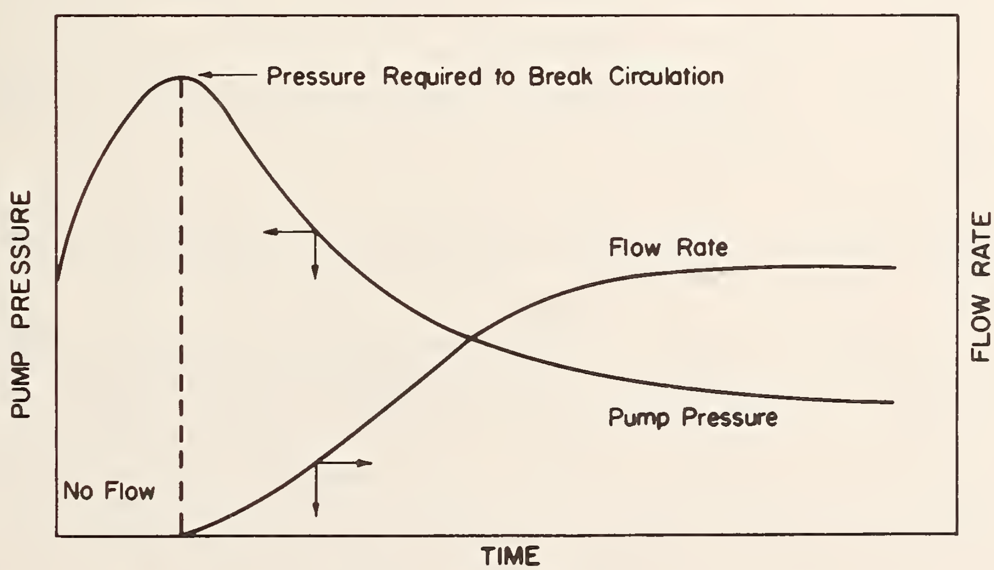


FIGURE F.1b PUMP PRESSURE AND FLOW RATE FOR A THIXOTROPIC FLUID (DIAGRAMATIC) (After IMCO, 1974)

(lb/100S ft. = 0.4788 n/m^2)

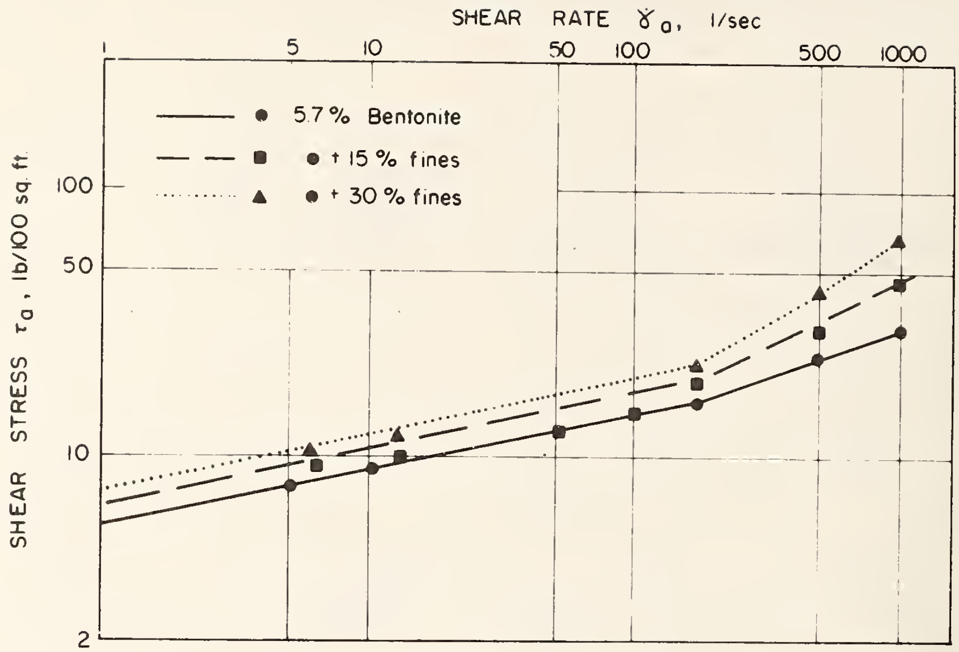


FIGURE F.2 RHEO-PLOT FOR A 5.7 % BENTONITE-WATER DRILLING MUD

This log form idealization shown in Figure F.2 is known as the power law, $\tau = K(\dot{\gamma})^n$. Therefore, the generalized Reynold's number becomes

$$N'_R = \frac{D^n V^{2-n}}{K^*} \rho_f$$

where $K^* = K\,(8^{n-1})\,(\frac{3n+1}{4n})^n$ (empirical)

ρ_f = density of drilling mud

D = average diameter of the wetted area $(d_1^2 - d_2^2/d_1+d_2)$

and V = velocity

Knowing the Reynold's number and "n" and "k", one can calculate the head losses in both the drill pipe and return annulus with Newtonian fluid mechanics concepts.

Data for Figure F.2 were obtained with a fan viscometer (Milchem, 1975) model 34. Mr. Michael Lawrence of Milchem provided the rheological data for a 21 lb (9.5 kg) per barrel (120 l) (5.7% by weight) bentonite slurry. This plot contains the $\tau - \dot{\gamma}$ data for the 5.7% slurry plus 15% and 30% (by weight) concentration of cuttings. The cuttings were simulated with inert "Martins ball clay" (clay sized SILT). Use of small-sized cutting material was necessitated by the small separation gap between the fan cylinders.

The generalized Reynold's number and the rheological data in Figure F.2 form the basis for all of the following calculations.

F.3 ANNULAR BIT PRESSURE (ECD)

During drilling, the mud circulates; therefore, pressure at the bit annulus must be greater than the static mud pressure. The pressure increase results from the flow resistance in the annulus. Annulus pressure during drilling for a given hole length can be calculated in terms of mud density and is called the equivalent circulating density (ECD):

$$ECD = \frac{\gamma_f z + \Delta Pa}{z}$$

$$= \gamma_f + \frac{\Delta Pa}{z}$$

where γ_f = mud unit weight

ΔPa= annular pressure loss from bit to collar

z = depth in ft

The derivation of this formula can be found in handbooks for drilling mud technology, i.e. IMCO (1974), Milchem (1973).

In the calculation of the maximum pressure of the mud, the ECD with cuttings suspended in the drilling mud should be employed. The presence of cuttings will increase both γ_f and Δ Pa. Average $\Delta\gamma_f$'s can be calculated from a combination of the penetration rate and the fluid flow rate and changes in Δ Pa by changes in the rheology.

If the drilling operation is stopped and started again, a higher pump pressure than that necessary to maintain flow will be required to initiate flow. This pressure build-up results from thixotropic characteristics of bentonite mud. The pressure required to "break circulation" (i.e. initiate flow) in the annulus might be higher than the ECD, but only lasts for a short time. Accurate calculations for a given mud annulus size and flow rate will reveal which pressure is higher and critical for fracturing the ground and loss of circulation.

Due to the impact of the drilling mud jetting from bit nozzles (the sudden 180 degree change in flow direction), the pressure in front of the bit will be even higher than the ECD during drilling. If the flow rate is high, a cavity can be eroded in front of the bit as discussed in Appendix D. Dump valves between the motor and bit (valves letting slurry out in the annulus with uphole flow direction) might be employed to prevent impact. See Figure I.1 for a schematic drawing of a dump valve.

An example calcultion will be made to determine the ECD for the 2 3/8 in. (6 cm) Dyna-Drill system in a 1000 ft (305 m) hole with no cuttings. The annular flow velocity

$$Va = Q/_A = \frac{32\ gpm}{2} \Big/ \frac{\pi\, d_{hole}^{\ 2} - d_{pipe}^{\ 2}}{4} = 1.09\ ft/sec$$

Therefore the strain rate (Milchem, 1975)

$$\dot{\gamma} = \frac{2.4\,Va}{d_{hole} - d_{pipe}} = 95 \text{ sec}^{-1}$$

For the region of $\dot{\gamma} = 95 \text{ sec}^{-1}$ in Figure F.2, n = .213 and K = 5.4 lb/100 ft^2. Therefore

$$K^* = (.05 \text{ lb/ft}^2)\,(8^{-.787})\,\left(\frac{(3)(.213)+1}{4(.213)}\right)^{.213}$$

$$= .011 \text{ lb/ft}^2$$

Therefore the Reynold's number is

$$N'_R = \frac{(.177)^{.213}\,(1.09)^{1.787}}{.011} \quad \frac{65.8}{32}$$

$$= 149$$

Since $N'_R < 2000$ the flow is laminar. The maintenance of laminar flow in the annulus is important for hole stability.

The pressure loss along a horizontal pipe was calculated using the Darcy-Weisbach equation:

$$\Delta Pa = \gamma_f h_f = f\,\frac{L}{D}\,\frac{Va^2}{2g}\,\gamma f$$

where

$$f = \frac{64}{N'_R}$$ is an empirical friction factor for laminar flow. (Graf, 1971)

$$\Delta Pa = \frac{(64)(1000)(1.09)}{(149)(.177)(64.4)} \quad \frac{65.8}{144}$$

$$= 19 \text{ psi/1000 ft}$$

This head loss calculation would be larger by a factor of 2 if calculated with formulae from the mud distributor's work books.

This same procedure was followed with the formulae from Milchem's handbook (Milchem, 1975) for the four systems at various depths and hole lengths. The resultant ECD's are presented in Figure F.3. The total ECD's are still predominantly a result of the static head.

F.4 CUTTINGS TRANSPORT

As shown in the rheology section, the transport of cuttings will increase the intercept but not the slope of the log τ vs log $\dot{\gamma}$ plot. The increase in ECD resulting from the transport of cuttings constituting 15% of the clurry by weight has been calculated and is plotted for the 1000 ft (305 m) 2 3/8 in. Dyna-Drill example in Figure F.3. The γ_f increases to 72 lb/ft^3 (8.9 N/m^3); however, the increase in K decreases N'_R and the ΔPa previously calculated increases to 26 psi/1000 ft. This ΔPa does not correspond to that in Figure F.3 because of the differences in calculational approach. The above calculational example serves as a

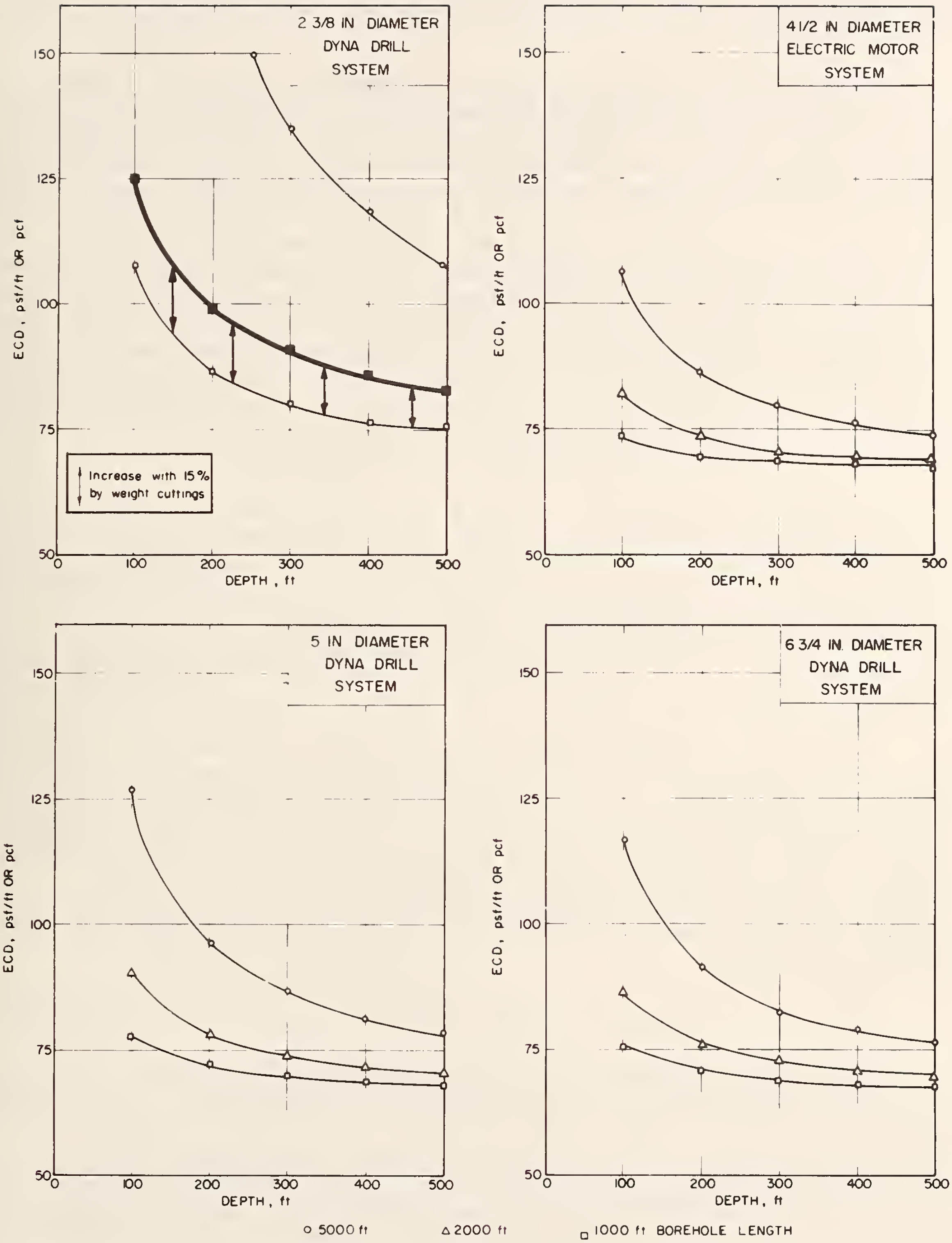


FIGURE F.3 EQUIVALENT CIRCULATING DENSITIES FOR FOUR PENETRATING SYSTEMS (No Cuttings)

(1 in. = 2.54 cm) (1 ft. = 0.305 m) (1 pcf = 16.01 kg/m^3)

means of discussing the fluid mechanics behind the phenomenon. Those data in Figure F.3 were determined through procedures outlined by Milchem (1975).

To determine the range in the concentration of solids, a penetration rate must be assumed for both the mandrel and thruster systems. That rate was assumed to range between 60 to 150 ft/hr (18-46 m/hr) on the average. With that assumed advance rate, the concentration of cuttings by weight ranges from 5 to 13% for the 4.5 in. (11.4 cm) hole and 16 to 37% for the 7 in. (17.8 cm) hole. The advance rate will have to be carefully controlled to maintain an ECD which precludes hydraulic fracture. See Section F.6 for detailed discussion of hydraulic fracture. Since the annular fluid flow rates for the larger holes are low, they can be significantly increased. If the increased fluid is released by the dump valves already mentioned, the concentration can be reduced. For simplicity of comparing the systems, a 15% concentration of cuttings will be assumed. This assumption will result in essentially the same magnitude ECD increase for cuttings transport for all of the systems.

In order to determine the effects of settling with time, fan viscometer tests were continued for 2 hours. The viscometer rotates about a vertical axis, and the fines will settle vertically. If significant settling would occur, the $\tau/\dot{\gamma}$ ratio should decrease with time as the material settled out. After 2 hours of rotation at $\dot{\gamma}$'s of 100 1/sec, there was only a slight change in $\tau/\dot{\gamma}$, which indicates that there will be no significant settling of clay sized silt during transport.

A more exact modeling employing sand should be conducted. However, these particle sizes are not compatible with presently available viscometers. Horizontal pipeline test simulations should be undertaken to determine the head loss — % concentration of cuttings relationships more exactly. The model tests performed, however, do indicate that cuttings transport will be under laminar flow conditions. Incremental head losses will be largely a function of the increased slurry density and no settling of inert (clay sized) silt should be expected.

F.5 TOTAL CIRCULATION PRESSURE LOSSES

The mandrel system for these calculations was the 2 3/8 in. (6 cm) O.D. Dyna-Drill with a 4 1/2 in. (11.4 cm) bit and a 2 3/8 in. (6 cm) O.D. drill pipe in Table F.1. The drill pipe was assumed smooth for all of the Reynold's number calculations. The Darcy-Weisbach equation was used to calculate the pressure loss (with 15% cuttings) where the "D" factor was taken as four times the cross sectional area divided by the total wetted perimeters. The friction factor was calculated with an empirical relationship for laminar flow.

The pressure loss in the surface equipment will be minimal in comparison to the inhole pressure loss because only a small size mud

pump and short distances of connection hose and connections are needed. Therefore, for both the mandrel and the thruster, the surface equipment pressure loss will be assumed to be approximately 15 psi (104 kN/m^2).

In Table F.2 the pressure losses for the mandrel system are summarized for various hole lengths. Included in this table is an estimate of the pressure drop across a 4 1/2 in. (11.4 cm) diamond or drag bit. In addition, there is an estimation of the maximum pressure rating for the mud pump which is 50% above the total pressure loss.

Calculation of the Reynold's number with both a 1 in. (2.5 cm) and a 2 in. (5.0 cm) ID conduit will indicate the type of flow occurring. Typical strain rates are 1872 sec^{-1} and 936 sec^{-1}. Therefore from Figure F.2, n = .5 and k = .004 lb/ft^2 for the 5.7% bentonite slurry. Typical slurry velocities within the pipes are 13 and 6.5 ft/sec (2.0 m/sec) for the 1 in. and 2 in. pipes respectively. Therefore

$$N'_R = \frac{(1/12)^{.5}\ (13)^{1.5}}{.004} \cdot \frac{65.38}{32.2}$$

$$\simeq 6800$$

which is turbulent. Likewise N'_R for the 2 in. cable is 2805 and is turbulent also.

Therefore flow down the drill pipe is characterized as turbulent and flow back up the annulus is laminar.

Important dimensions and characteristics of the example thruster system are:

Thruster Diameter: 5.75 in. (14.6 cm)

Cable: 2 in. (5.1 cm) O.D.
Containing 3 hoses--One 1-in. (2.54 cm) O.D. and
Two ½-in. (1.3 cm) O.D.

Hydraulic Motor: 10 H.P., 30 GPM, 300 RPM
Length--4 ft (1.22 m)
Diameter--5 in. (12.7 cm)

Modified Coring Bit: 7 in. (17.8 cm)

The pressure losses for the thruster have been calculated in the same manner as the example calculations for the mandrel system and are summarized in Table F.2.

Only one calculation requires special attention in Table F.2. The value for the pressure drop across the hydraulic motor was calculated by:

$$\Delta P\ (\text{psi}) = \frac{\text{H.P.}}{\text{GPM}} (1714) \quad \text{(Dyna-Drill, 1975)}$$

for this particular motor,

$$\Delta P\ (\text{psi}) = \frac{10}{30}\ (1714) = 571\ \text{psi}\ (3940\ \text{kN/m}^2)$$

TABLES F.2 AND F.3: PRESSURE LOSSES (PSI) IN MANDREL AND THRUSTER SYSTEMS

	F.2					F.3				
	MANDREL Drill Hole Length (ft)					THRUSTER Drill Hole Length (ft)				
Equipment	1000	2000	3000	4000	5000	1000	2000	3000	4000	5000
Mud Pump, Hoses Connections,	15	15	15	15	15	15	15	15	15	15
2 3/8 in. Drill Pipe, Joints (Internal Flush) Drill Collar (1.995 in. I.D.)	26	52	78	104	130	149	298	447	596	745
2 3/8 in. O. D. Dyna-Drill	600	600	600	600	600	571	571	571	571	571
4 1/2 in. Diamond or Drag Bit	50	50	50	50	50	60	60	60	60	60
TOTAL Equipment ΔP_c	691	717	743	769	795	795	944	1093	1242	1391
Annulus Pressure Loss ΔP_a	55	110	165	220	265	21	42	63	84	105
TOTAL Pressure Loss (psi)	746	837	908	989	1060	816	986	1156	1326	1496
Required Maximum Pressure Rating for Mud Pump	1075	1150	1225	1300	1425	1250	1550	1825	2125	2400

(1 ft. = 0.305 m)
(1 in. = 2.54 cm)

F.6 HYDRAULIC FRACTURE

The so-called "loss of circulation" can occur in two different ways: (1) Drilling mud flows away from the borehole in very permeable soil strata, such as coarse sand or gravel, or (2) The pressure in the drilling mud is so high that the ground is fractured and drilling mud is lost through the fracture.

Loss of mud through permeable soil can be prevented with additives or high bentonite concentration as discussed in Appendix H. It is important to get the additives downhole as soon as possible to build a filter cake and prevent caving of the borehole wall (see Figure H.3).

Estimation of the mud pressure that will fracture the ground requires knowledge of the stress distribution around the borehole, and the "tensile" strength of the soil. In oil drilling technology, the term "fracture gradient" is commonly used. This term denotes the mud pressure at a certain depth below the surface required to fracture the ground, divided by that depth. The fracture gradient could be expressed in effective stress in the following way:

$$F_g = u/z + X\bar{\sigma}_v/z$$

where: $\bar{\sigma}_v$ = vertical effective stress

X = stress coefficient for fracture

μ = static porewater pressure

z = depth

Pore pressure and vertical stress can usually be estimated fairly well when the groundwater table elevation and soil density is known. The stress coefficient is, however, more difficult to obtain. In typical oil drilling areas (e.g. the Gulf Coast) curves for the stress coefficient with depth are established from case studies. However, these curves are only valid for vertical boreholes in the specific areas.

For horizontal boreholes it is necessary to find an expression for X. Marr (1974) gives the fluid pressure required to fracture soft ground from vertically oriented piezometers:

$$\sigma_f = \sigma_3 + \sigma_t$$

where: σ_3 = Minor principal stress

σ_t = Soil "tensile" strength.

It is expected that the fracture pressure in horizontal boreholes have the same basic form:

$$\sigma_f = \sigma_{min} + \sigma_t$$

where: σ_{min} = smallest normal stress on any plane in the soil around the borehole.

The stress distribution around the borehole is characterized by high circumferential stress, with the radial stress dependent mainly upon internal pressure. (See Appendix H for stress distributions.)

The elastic solution taking borehole distortion but not compression into account (Peck, 1969) gives the radial stress in terms of the total stress K_{OT} (σ_H/σ_V).

$$\sigma_r = \frac{1}{2}\sigma_v(1 + K_{OT})$$

The axial stress, σ_a, associated with this solution will vary slightly from $K_{OT}\cdot\sigma_v$

An examination of the available theory allows the assumption:

$$\sigma_{min} = \sigma_a > \sigma_H = \bar{\sigma}_v K_o + u$$

K_o will be defined as $\bar{\sigma}_H/\bar{\sigma}_V$ for the remainder of the appendix. It is not certain how much larger σ_{min} is than the horizontal stress at rest. Intuitively it can be estimated at 10-30%, which then will provide a conservative element in the design for hydraulic fracturing when σ_{min} is assumed to be equal to σ_H.

The fracturing pressure will then be:

$$\sigma_f = \sigma_H + \sigma_t = K_o\bar{\sigma}_v + u + \sigma_t$$

Field tests in Boston blue clay and Chicago clay as presented in Table F.4 give fracturing pressures σ_f and soil pressure by closing of the fracture σ_3. In Boston blue clay σ is 20-25% of σ_3, in Chicago σ_t is approximately 120% of σ_3. As a first approximation, the average of the apparent tensile strength divided by the normalized undrained shear strength is assumed to be 2 for both clays.

The fracturing pressure will then be

$$\sigma_f = u + (K_o + 2\,\frac{s_{u\,av}}{\bar{\sigma}_v})\,\bar{\sigma}_v$$

Comparing this formula with the expression for the fracture gradient presented earlier in this section:

$$F_g = u/z + X\bar{\sigma}_v/z$$

TABLE F.4: CRACKING AND CLOSE-UP PRESSURES (kg/cm^2)
(after Marr, 1974)

LOCATION	PIEZ No.	ELEV.	σ_3	σ_f	$\sigma_f-\sigma_3$	$s_{u\ av}$	$\frac{\sigma_f-\sigma_3}{s_{u\ av}}$
STA 263	1	-56.5	3.61	4.72	1.11	.40	2.8
	2	-53.5	4.15	5.0	.85	.40	2.1
	3	-35.5	3.09	4.05	.96	.45	2.0
	4	-57.5	4.23	5.07	.84	.34	2.5
	5	-78.5	5.49	6.45	.96	.25	3.8
	6	-40.5	3.15	4.34	1.19	.44	2.7
	7	-38.5	2.40	3.16	.76	.44	1.7
	8	-58.5	3.63	4.24	.61	.32	1.9
	10	-22.7	2.17	2.75	.58	.44	1.3
	11	-59.8	3.56	4.64	1.08	.32	3.4
	13	-51.7	3.49	4.19	.70	.40	1.8
	14	-73.1	4.84	5.40	.56	.25	2.2
	15	-23.6	1.69	2.87	1.18	.49	2.4
CAES	3	-77.6	4.46	4.96	.50	.43	1.3
	7	-15.4	1.84	2.57	.73	.42	1.7
LIFE SCI.	2	-15.7	2.19	2.76	.57	.75	.8
	4	-68.5	3.59	4.11	.52	.30	1.7
	6	-60.3	3.30	4.29	.99	.25	4.0
STUDENT CENTER	1	-20.3	2.06	2.66	.60	.51	1.2
	2	-34.3	2.59	3.21	.62	.62	1.0
	4	-62.6	3.52	4.14	.62	.24	2.6
	5	-19.3	2.06	2.72	.66	.51	1.3
	6	-33.2	2.72	3.45	.73	.65	1.1
	7	-47.2	3.10	3.78	.68	.43	1.6
	8	-61.6	3.45	3.93	.48	.24	2.0
SPACE CENTER	1	-38.	2.35	3.23	.88	.55	1.6
	2	-72.9	3.99	4.67	.68	.25	2.0
CHICAGO	1	-18	1.00	2.57	1.57	.51	3.2
	2	-45	3.12	7.81	4.69	1.47	3.2
	3	- 6	.56	1.48	.92	.46	2.0
	4	-18	1.11	2.27	1.16	.51	2.4
	5	-18	1.19	2.88	1.69	.51	3.2

reveals that the stress coefficient may be approximated as

$$X = K_o + \frac{2\, s_u \text{ av}}{\bar{\sigma}_v}$$

for horizontal boreholes.

In cohesionless soil the fracture gradient is therefore approximately

$$F_g = \frac{1}{z}\,(u + K_o\bar{\sigma}_v)$$

and in cohesive soil

$$F_g = \frac{1}{z}\,(u + 2\, s_u \text{ av} + K_o\bar{\sigma}_v).$$

Figure F.4 is a plot of the fracture gradient with depth in different "typical" soils. It is based on $\sigma_{min} = \sigma_H$ and $\sigma_t = 2\, s_u$ av.

An example calculation shows the following results: Sand, GWT at 30 ft (10 m), $K_o = .5$, $\gamma_{dry} = 112$ pcf (1.8 g/cm^3), $\gamma_{total} =$ 125 pcf (2.0 g/cm^3), z = 100 ft (30.5 m):

$$F_g = \frac{1}{z}\,(u + K_o\bar{\sigma}_v)$$

$$= \frac{1}{100}\,\{(70 \cdot 62.4) + .5\,(112 \cdot 30 + 62.4 \cdot 70)\}$$

$$= 81 \text{ psf/ft.}$$

F.7 CABLE FRICTION

Minimum cable friction for the thruster system will result from the annular drag forces of the slurry flowing past a neutrally buoyant cable or pipe. These drag forces are calculated with a 2 3/8 in. (6.0 cm) diameter steel drill pipe in a 4 1/2 in. (11.4 cm) hole. The relative velocity is essentially the annular fluid velocity which is 1.09 ft/sec (0.33 m/sec). The Reynold's number, calculated in F.3, is 149.

The drag force is $\quad 1/2\,\rho\,(\frac{1.28}{N'_R})V^2\,S$

Where "S" is surface area per linear foot of cable or pipe and is 0.62 ft^2/ft (0.06 m^2/m). Substituting the appropriate system parameters into the above equation, the drag force is calculated as 0.06 lb/ft (.87 N/m).

Similar calculations were made for the 4 1/2 in. (11.4 cm) electric motor and 5 in. Dyna-Drill systems with the resulting minimum drag forces of .01 lb/ft (.15 N/m) and .11 lb/ft (1.59 N/m) respectively.

The above drag forces are the absolute minimum and result only from fluid drag. As such the forces implicitly assume a neutrally buoyant

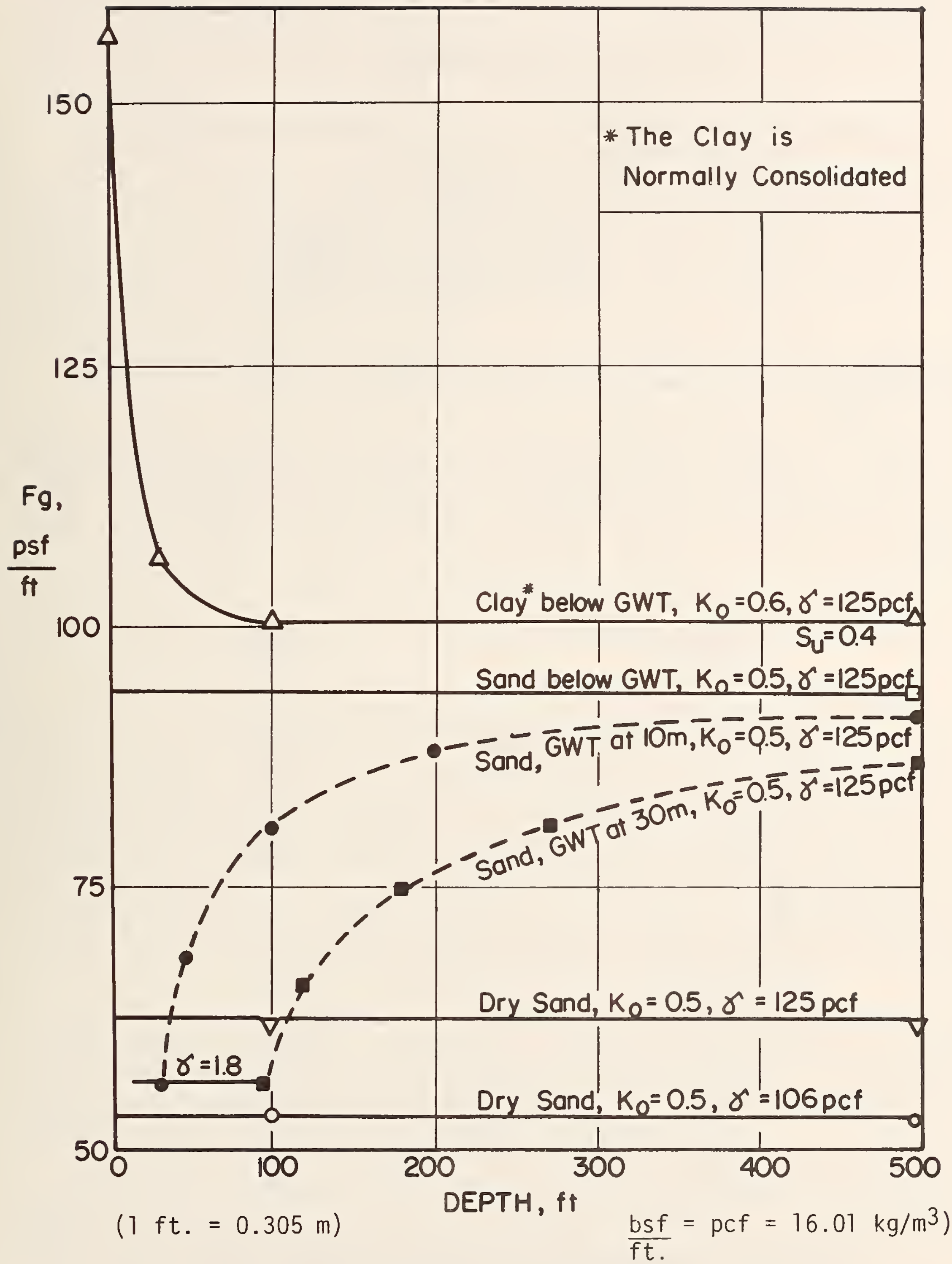


FIGURE F.4 FRACTURE GRADIENT (HYDRAULIC FRACTURE PRESSURE /DEPTH) IN DIFFERENT SOILS

cable. If the cable (or pipe) is not neutrally buoyant, then the drag forces will be much greater. See Appendix G for further details.

F.8 FILTER CAKE EROSION

Annular slurry velocities for the four excavation systems are:

System Number	Velocity (Va)
1	65.4 ft/min (0.33 m/sec)
2	16.3 ft/min (0.08 m/sec)
3	122.5 ft/min (0.62 m/sec)
4	85.8 ft/min (0.44 m/sec)

Even higher velocities might occur at certain areas where instrumentation packages, etc., occupy more of the annular space than the drillpipe or cable.

Figure F.5 shows the distribution of annulus (laminar) flow velocity for different n-values. The velocity at the borehole wall (filter cake surface) is zero, but rapidly rising, especially for low n-values. More

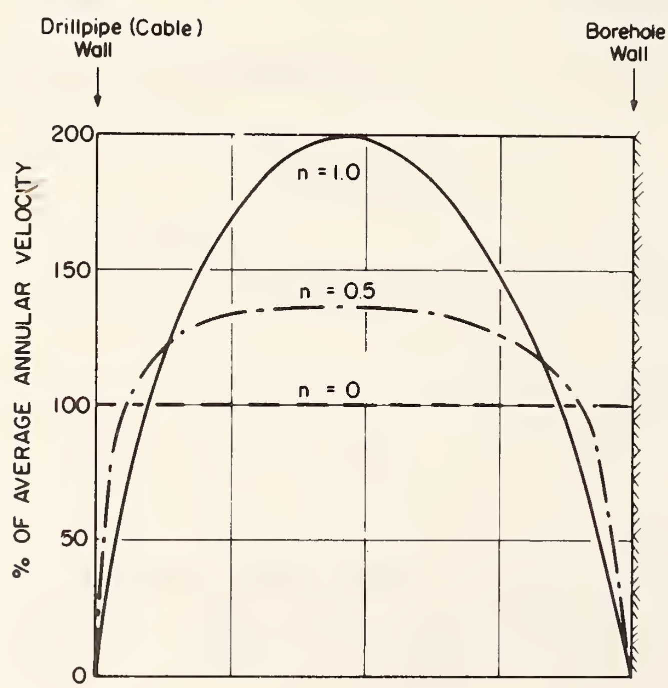


FIGURE F.5 DISTRIBUTION OF ANNULAR FLOW VELOCITY FOR DIFFERENT "n"- VALUES

importantly, the shear stresses on the walls are lowest for lower n's. Previous calculations have shown the annular flow to be laminar. System 3, with the greatest annular flow velocity has a Reynold's number (N'_R) of 936, well below that indicative of turbulent flow conditions (Graf, 1971).

The return flow for the different excavation systems will thus primarily be laminar. This laminar flow should not erode the filter cake. Greater n-values are commonly employed in oil well drilling, and do not erode the filter cake. In slurry trench excavation with clamshell, the clamshell is constantly pulled up and down along the filter cake. This movement will cause high slurry velocities and perhaps turbulence along the wall.

Graf (1971) has compiled a number of measurements of the critical fluid velocity (or critical shear stress) below which no scour will occur. Studies with cylinder viscometers indicate that critical fluid shear stresses for remolded cohesive material are on the order of .2 lb/ft^2. Reference to Figure F.2 will show that shearing stress exerted by the slurry are also approximately .2lb/ft^2. However, other experiments indicate fluid velocities of at least 1.2 m/sec (4 ft/sec) are necessary for erosion of cohesive soil. Velocities of the proposed systems range from 0.08 to 0.62 m/sec (.27 - 2.0 ft/sec). Together these results indicated that cohesive materials will be just stable.

Possibly the simplest means of discussing the erosion susceptibility of cohesionless materials is still Hjulström's (1935) chart reproduced as Figure F.6. This chart indicates that critical erosion and deposition velocities of turbulently flowing clear water are not the same because additional shear stresses are necessary to overcome capillary forces and surficial laminar layers. The position most susceptible to erosion is the crown of the horizontal hole because it will not be protected by a bed load. The critical erosion velocity is approximately 0.2 m/sec (.6 ft/sec) when the flow is turbulent. This velocity indicates that fine sands may initially erode. However, if the filter cake becomes established, then the erosion should decrease.

Most tests for erosion susceptibility of soils have been conducted with turbulently flowing clear water. Since the borehole will be filled with laminarly flowing bentonitic slurry, the above quoted tests are not strictly applicable. They do indicate that control of erosion is possible within the range of available equipment.

Field tests with horizontal drilling equipment could give some answers to the erosion problem. In addition, laboratory tests with rotating cylinders (similar to that employed by Arulanandan, 1975) could check erosion rates of the wall soil and/or the filter cake.

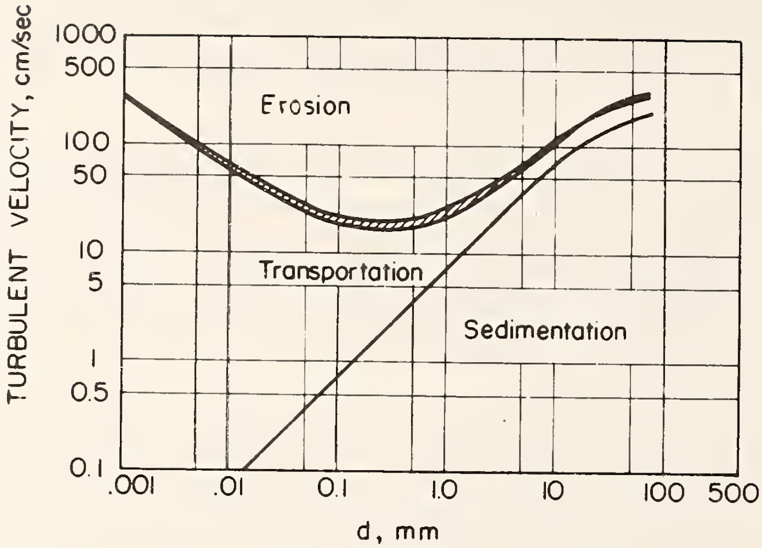


FIGURE F.6 EROSION - DEPOSITION CRITERIA TURBULENTLY FLOWING CLEAR WATER (After Hjulström, 1935)

F.9 DRILLING FLUID RECIRCULATION METHODS

The amount of drilling fluid returning to the surface is a function of both soil type and equipment. A typical recirculation system used in rural and open work areas is shown in Figure F.7. Where hydraulic fracturing occurs, drilling fluid may not return to the surface. Problems associated with loss of circulation are numerous, and procedures to follow when circulation is lost can be found in most slurry company catalogs.

Figure F.7 is a schematic drawing of the desanding recirculation system used by Titan Contractors for the Cerritos Channel crossing. Drilling mud was pumped into the drill pipe and returned to the surface either through a washover pipe or occasionally through the drill hole annulus and collected in the earth pit. This earth pit or holding tank had enough volume to hold drilling fluid equal to the anticipated maximum volume of the drill hole. The pit detains the drill fluid for a sufficient time to allow large particles to settle to the bottom.

Sand-sized particles did not settle out in a reasonable amount of time and were separated from the fluid with a shaker. This retention is a positive factor for transport but negative for releasing the cuttings.

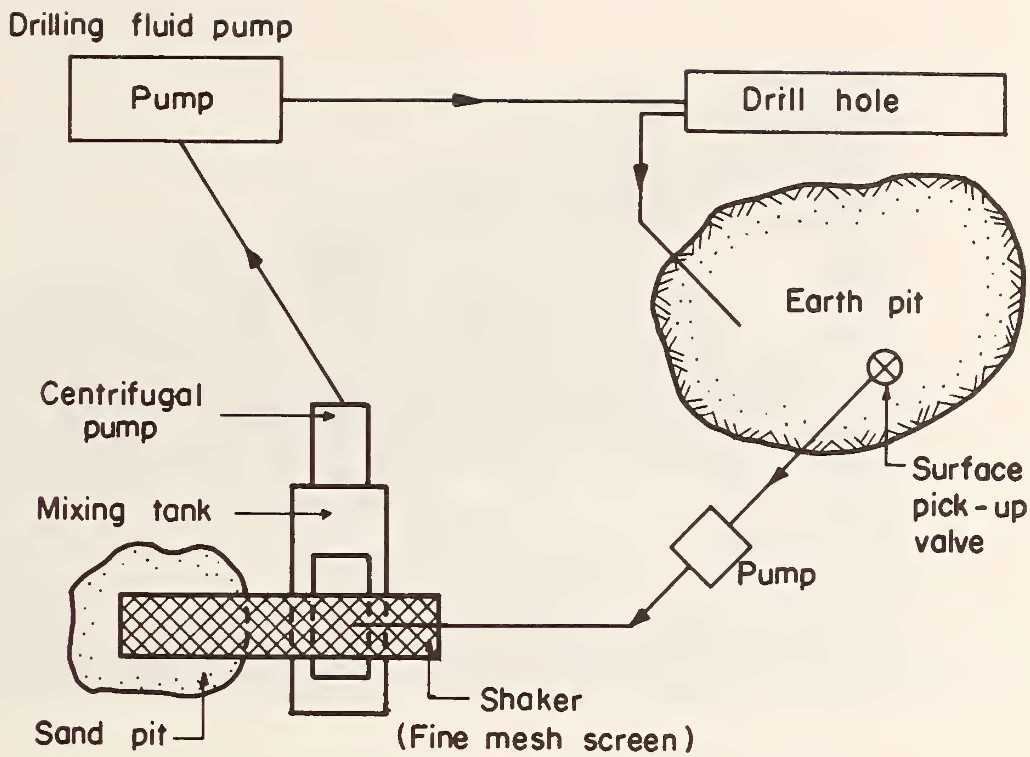
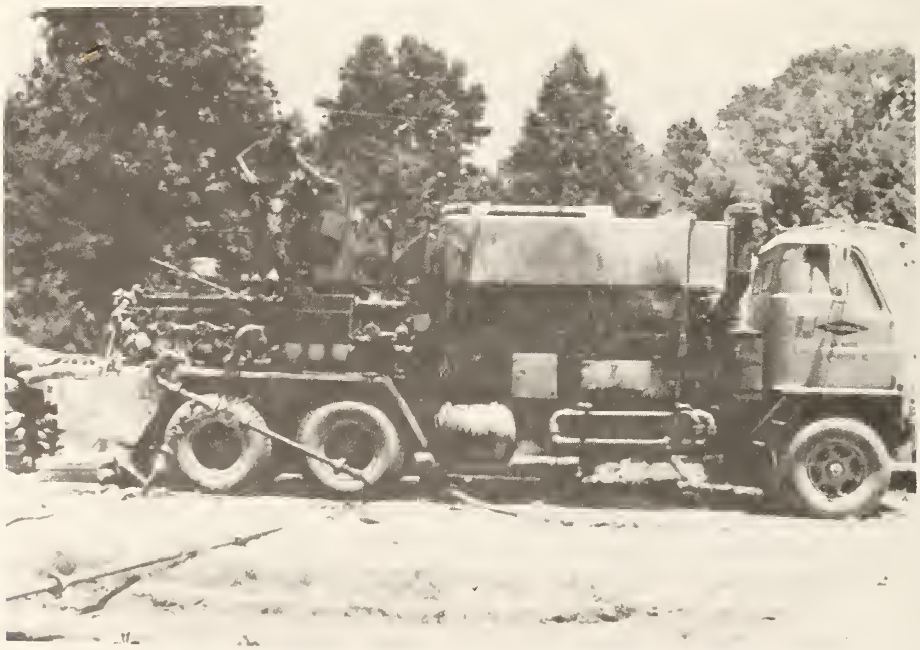


FIGURE F.7 DESANDING RECIRCULATION SYSTEM

The shaker was a fine mesh (usually #80 - #100 sieve) slanted over the mixing tank. The fluid passing the sieve is recollected in the mixing tank while the sand was carried away to the sand pit on the conveyor. The recycled drilling fluid is then blended with additional mud, additives, and water. From the mixing tank the fluid was returned to the mud pump. The operational space was not a problem at this site. More details concerning treatment of hydraulically-mined slurries can be found in another report to be completed by early 1976 entitled "Hydraulic Transportation and Solids Separation of Excavated Materials in Tunnels" (Nelson, 1975).

When operational space is limited, mud recirculation systems on flatbed trailers, such as that shown in Figure F.8, can be employed. Mud recirculation and treatment is a specialized segment of the petroleum industry. Therefore, each specific application is a custom order. A typical mobile recirculation system for use with a 2 3/8 in. (6 cm) O.D. Dyna-Drill mandrel penetrator might include a mixer with twin centrifugal pumps, a carriage mounted mud pump, and a 9000 gal (34,200 dm^3) settling tank. The entire system would be closed and could easily be adapted for use in an urban environment.

a) MOBILE DRILLING MUD STORAGE TANKS



b) MOBILE DRILLING MUD PUMP AND MIXING TRUCK

FIGURE F.8 A PORTABLE MUD RECIRCULATION SYSTEM

APPENDIX G

PERFORMANCE OF HORIZONTAL PENETRATION HARDWARE IN SOFT GROUND

G.1 INTRODUCTION

To treat the interaction between the hardware and the material to be penetrated--soft ground--several key issues must be investigated in depth. For background, present approaches to directional control will be discussed (G.2), followed by influence of geology upon directional drilling (G.3). Details of equipment interaction are broken into: (1) required soil strength for thrusting downhole (G.4); (2) safe bearing pressures for anchor pads and deflection shoes (G.5); (3) hole friction for the mandrel system (G.6); and (4) hole friction for the thruster system (G.7). The appendix is concluded with two sections: determination of minimum radii of curvature for the two systems and the relationship of the radius of curvature to object avoidance (G.8); and dimensional analysis of hardware-soil interaction (G.9).

G.2 APPROACHES TO DIRECTIONAL CONTROL

Any long hole must be a directionally-controlled hole, whether it is horizontal or vertical. Therefore, much of the directional control methodology for horizontal penetration is a natural extension of experience in the control of vertical rotary-drilled holes. The following discussion deals with forces at the bit. Therefore, the rotation of the drill string is of little importance.

Control of bit deviation is a function of the relative magnitudes of the normal force, F_N, and the side force, F_S, shown in Figure G.1a. In horizontal boring the normal force is developed by the out-hole carriage or the in-hole thruster. The side force is developed by gravity, leverage of the drill string with the stabilizer (deflection pad, bent housing or bent sub) acting as a fulcrum, the reaction of an extended deflection shoe, or the rotational bit reaction. Schematic representations of these four components are given in Figure G.1b.

For leveraging, the fulcrum can be a bent sub, bent housing with blading opposite the face for increased leverage, a bent Dyna-flex, or a deflection shoe. When the normal force is increased beyond that which is required for drilling, the drill pipe will bend just above the fulcrum point downward. This leverage then induces an upward side force at the bit.

The flexibility of the drill pipe immediately above the fulcrum point, the degree at which the fulcrum is prebent, and the effective normal force experienced at the fulcrum, will determine the angle

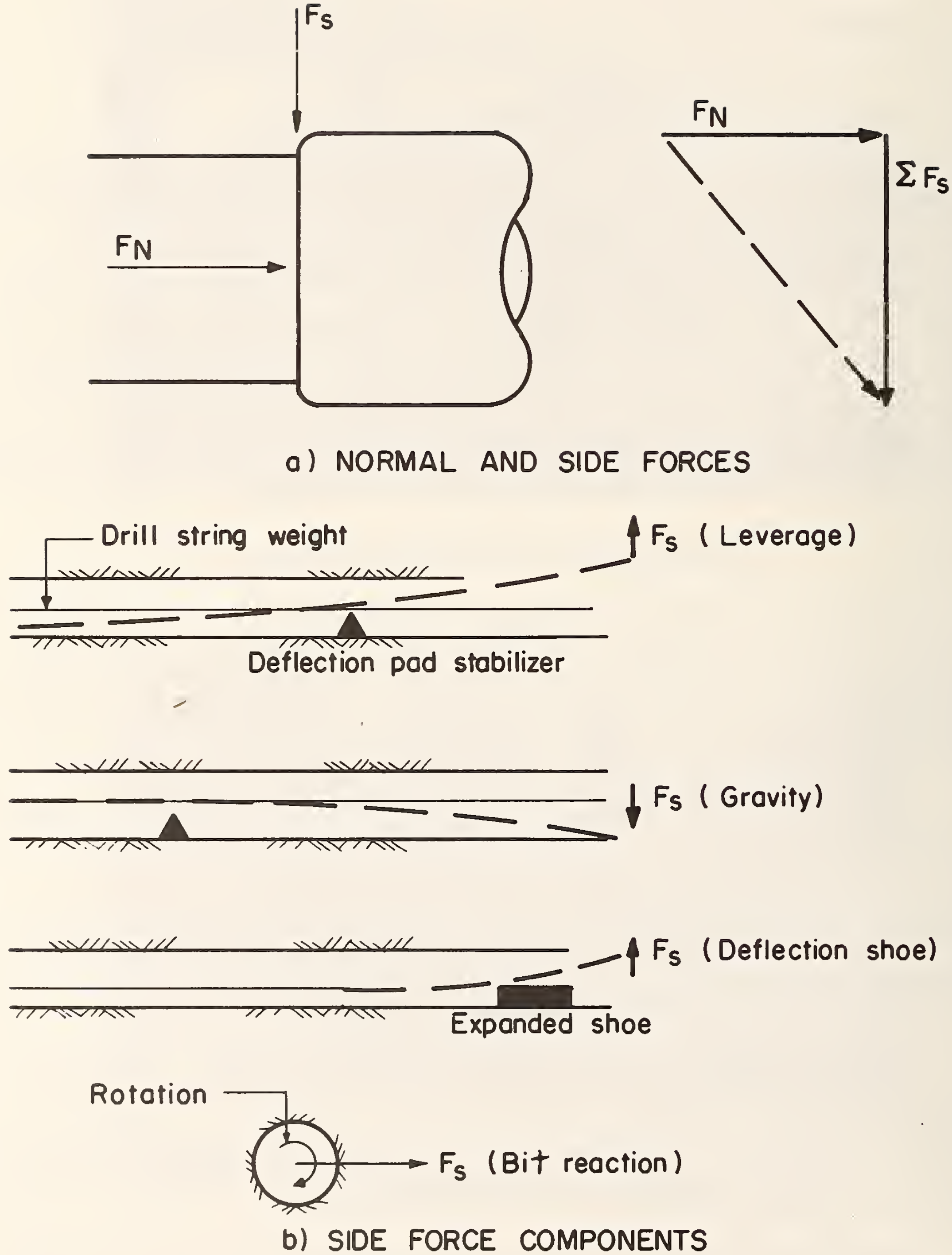


FIGURE G.1 CONTROL OF BIT DEVIATION

increase per length of drill hole. Angle change is usually stated with respect to 100 ft (31 m) intervals of course length.

If the normal force is decreased so that the advance rate slows, the exiting drilling fluid may partially erode or jet the hole at the face and the gravitational forces will cause the path to deflect downward. Control of the drill bit will be minimal unless a high penetration rate is maintained to decrease the erosion energy per unit volume of soil excavated.

Bit rotation deflects the path to the right for a clockwise rotation. This force is caused by grabbing of the bit and is similar to the deviation experienced when seating a hand-held drill.

The mandrel and thruster maneuverable penetrating systems (MPS's) employ separate mixtures of side forces to control direction. The mandrel MPS is a combination of a downhole motor and a bent sub, bent housing or articulated sub. The motor face must be directed upward and the required bit rotational speed and ratio of normal force to penetration rate must be maintained to counteract the downward deflection of gravity and the clockwise rotation of the drill bit. The downward deflection tendencies also effect the thruster MPS. Unlike the mandrel they are compensated by orientating a deflection shoe to the downward side of the hole and extending the shoe the necessary distance in order to maintain a horizontal course. The normal force is developed by the thrust applicator by jacking against the borehole walls.

G.3 INFLUENCE OF GEOLOGY

As with any other subsurface work, the type of geological conditions encountered will affect the choice of equipment. Therefore, in order to more effectively discuss the performance of the equipment that is available for horizontal directional drilling, geological conditions will be defined.

The range of urban geologies, listed in Table G.1, have been chosen as representative of the possible subsurface conditions that exist around the major cities in the United States. Soft clays and loose sand, Category A, would be difficult to penetrate because (1) their tendency to squeeze (clay) or run (sand) creates high pipe or cable friction, (2) the clay's tendency to adhere will clog the bit, and (3) low strengths will inhibit the development of side reactions necessary for directional control. On the other hand, stiff clay and dense sand would be relatively drillable because of (1) their relatively high strength which prevents hole collapse and enables the development of side reactions, and (2) their low resistance to abrasion which permits long bit life.

Residual soil, Category C, can have a wide grain size distribution which includes boulders and clay size particles. The problem-sized particles, pebbles ($\simeq \frac{1}{2}$ in./1.3 cm diameter), will bind a tricone roller bit and are too small for a drag bit to crush.

TABLE G.1: RANGE OF URBAN GEOLOGICAL CONDITIONS

Soil Parameters	Soil Categories: A — Saturated Soft Clay	A — Saturated Loose Sand	B — Saturated Overconsolidated Clay	B — Saturated Dense Sand	C — Residual Soil
γ_t (pcf)	85-100	85-100	115-140	115-140	125-130
D_r	---	20-30	---	>60-65	35-100
q_u (tsf)	0.10-0.50	---	0.50-2.0	---	Widely varying soil and rock
k(cm/sec)	10^{-6}	10^{-1} to 10^{-4}	10^{-7} to 10^{-8}	10^{-2} to 10^{-5}	10^{-2} to 10^{-7}
ϕ	---	30°	---	35°- 40°	---

Thus they will jam bits. In addition, the drilling fluid will probably not suspend the larger-sized particles for long fluid travel times. Therefore, in order to drill in residual soil, one must have a bit that will crush these pebbles and a drilling fluid that will keep them in suspension until they have exited the drill hole.

The maximum design-operating depth for the MPS will be 500 ft (153 m) below the ground surface. Therefore, a large percentage of the drill hole will be below the water table. This deep operational depth will require all of the equipment to be designed for immersion in water to depths of 500 ft (153 m).

Since the maximum design operating distance is 5000 ft (1525 m), certain effects on the MPS must be considered. At 500 ft (153 m) depths, and at a horizontal distance of 5000 ft (1525m), the MPS will have to overcome a sizeable amount of friction between the soil and the trailing equipment (e.g. drill steel or cable). Possible boundary conditions are discussed in Sections G.6 and G.7. The lubricity of the drilling fluid and the neutral buoyancy of the MPS and its trailing equipment will be a major factor in estimating this maximum operational distance. Drilling fluid drag forces were discussed in Appendix F.

Directional control of a horizontal drill hole is dependent upon the undrained strength of the saturated soil. This undrained shear

strength (S_u) is approximately one half of the unconfined compressive shear strength, as shown in Table G.2 for clays and silty clays. This table gives the boundary of the soil or soft ground strengths considered in this study.

TABLE G.2: SHEAR STRENGTH OF COHESIVE SOILS

(Terzaghi and Peck, 1967)

$S_u = 1/2\ q_u$ (tsf)	Consistency
0 - 0.125	Very Soft
0.125 - 0.25	Soft
0.25 - 0.50	Medium
0.50 - 1.0	Stiff
1.0 - 2.0	Very Stiff
> 2.0	Hard

The undrained shear strength will affect the turning radius for both of the MPS's and the bearing capacity of the anchor pads for the DRILCO thrust applicator and CONOCO's deflection shoe. The relationship between the undrained shear strength and the required resistance needed to deflect the MPS has not been rigorously analyzed to date. A rigorous solution of the relationship is beyond the scope of this study. However, it is informative to list possible boundary relationships for an MPS drilling in soft ground. Such a list follows:

(1) In soft to medium clay ($S_u \simeq 0.1 - 0.5$ tsf) it is hypothesized that the mandrel MPS will tend to crab along its path during turning. Crabbing occurs when the heading of the drill bit differs significantly from the direction of travel of the drilling unit. The MPS will crab until enough resistance from the soil is built up to react against the drill bit and create a side force large enough to change direction.

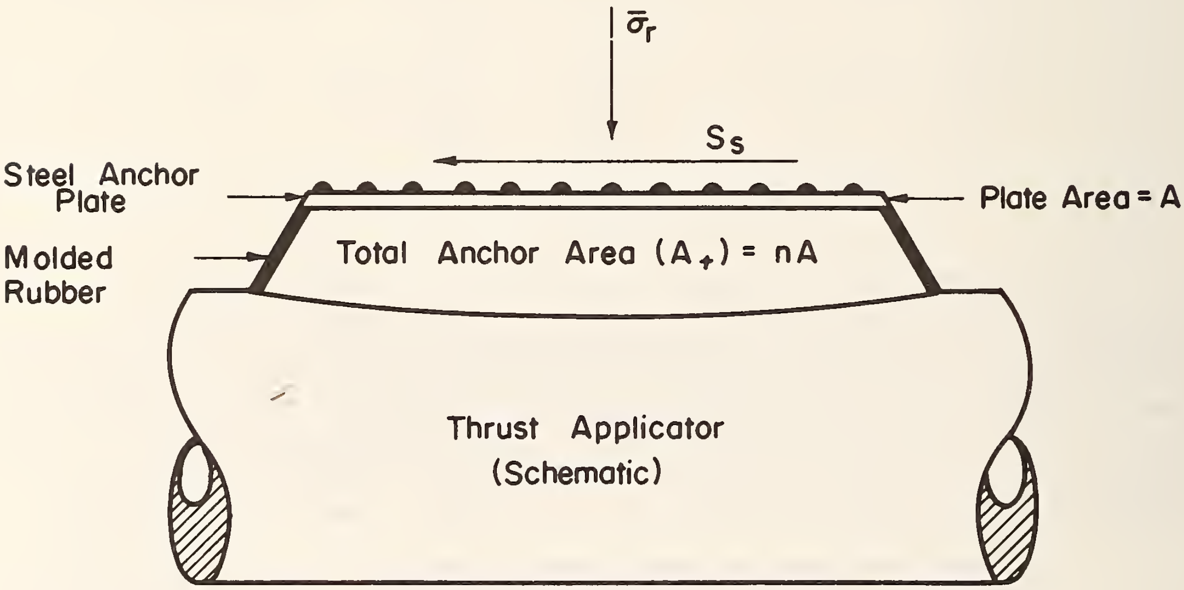
(2) In loose sand this crabbing effect is not expected to be as severe as that experienced in soft clay. During crabbing sand grains will have a tendency to densify or compact which will increase the bearing capacity and the side force responsible for turning.

(3) An overconsolidated clay or dense sand will have a high enough bearing capacity to provide the necessary resistance to cause turning without the MPS experiencing any crabbing.

(4) The MPS's drill path will also be affected by a change of soil conditions. For example, if the MPS is drilling in a medium (S_u = 0.5 tsf) clay with an upward inclined path and encounters a layer of dense sand, the drill bit will be deflected toward the horizontal.

G.4 REQUIRED SOIL STRENGTH FOR DOWNHOLE THRUSTING

The ability of the thrust applicator to supply thurst or pulling power is a function of the soil's shear resistance or strength along the anchor pads. The maximum shearing resistance will have to be reduced by a factor K (as shown in Figure G.2) to account for local bearing capacity failure and subsequent reduction of strength. Thus, the maximum thrust is dependent upon limiting local bearing capacity failures. See Section G.5 for further discussion.



SAND

$$S_s = k\,\bar{\sigma}_r \tan\Phi$$

CLAY

$$S_s = k\,C = k\,S_u$$

REACTION FORCE

$$F_s = A_+ \cdot S_s$$

FIGURE G.2 ANCHOR PAD SHEARING RESISTANCE

An estimate of S_s for a thrust or pulling force required has been made for two worst-conditions. The first case is the thrust required while the pads are anchored in soft ground with the drill bit encountering a boulder or pinnacle. In this case the minimum thrust necessary is on the order of 1000 lb (4450 N). The second case is the thrust required to drag the hoses over sand without significant lubricity (normally provided by the mud cake) or hose buoyancy from the drilling fluid. For cable pulling, it is desirable to develop the full pulling force, 7000 lbf (31,150 N) of the 8 in. thrust applicator. These two conditions were chosen because of the differences in the required normal forces.

For the 1000 lbf (4450 N) developed thrust, the total pad surface area required to operate the 5 3/4 in. thruster in the weakest clay (cohesive soil) environment is:

$$KS_u = 0.25 \text{ tsf} = 3.47 \text{ psi } (24 \text{ kN/m}^2)$$

$$A_t = F_s / KS_u = \frac{1000}{3.47} = 288 \text{ sq. in. } (1858 \text{ cm}^2)$$

as defined in Figure G.2.

The above calculation implies that 45 pads (pad dimensions 1.06 x 6 in. (2.7 x 15.2) cm) would be required for this soft clay soil with S_u = 0.25 tsf (24 kN/m^2). For a clay soil with KS_u= 2.o tsf (197 kN/m^2), the number of pads decreases to 5.6. Because of the complex interaction of the drill bit (jetting and cutting) and the soil, there is no reasonable analytical means of determining what the thrust requirements are in a total clay (no boulder) environment. The worst condition was analyzed; the required thrust should be less in a total soil environment.

A possible redesign was considered with a larger surface area for each anchor pad. The new pad size was estimated using the proportional relationship between two chords at different radii over the same arc degrees. Therefore, assuming a diameter of 8 in. (20.3 cm), the pad size might be 1.5 x 8 in. (3.8 x 20.3 cm) with a pad area equal to 12 sq. in. (77.4 cm^2).

An estimate of the minimum S_s required for various numbers of pads was then calculated for cohesive soils with a bit normal force requirement of F = 1000 lbf (445 N) and the relationship, $S_s = KS_u = F_s/A_t$.

TABLE G.3: MINIMUM REQUIRED SHEAR RESISTANCE

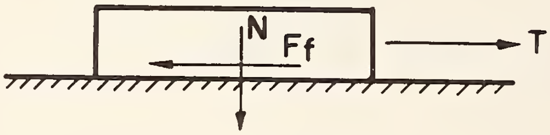
	Number of Anchor Pads					
	6	9	12	15	18	21
Minimum Required Shear Resistance tsf (kN/m^2)	1.0 (96)	0.67 (64)	0.50 (48)	0.40 (38)	0.33 (32)	0.29 (28)

Developing thrust in a stable hole of sand is not as great a problem as in clay. With the 1 by 6 in. anchor pad the maximum shearing resistance in loose sand for each pad could be as much as:

$$(\tan 20^{o})\ (25\ \text{tsf})\ (6/144)\ (2000) = 760\ \text{lb}$$

The maximum contact stress of 25 tsf (2400 kN/m^2) was obtained from comparisons of internal hydraulic pressures and piston areas with external anchor pad areas. This comparison is discussed further in Section G.5.

The same type of calculations were performed to estimate what minimum S_s would be required to pull the three thrust applicator fluid hoses along various hole lengths. These hoses were assumed to rest on the bottom of the hole in sand (i.e. worst condition possible, short of hole collapse). Therefore, the thruster must overcome the frictional force of the hose resting on sand without buoyancy, as shown in Figure G.3.



$$T > F_f = .4\ N$$

FIGURE G.3 FRICTION FORCES ACTING ON THRUSTER HOSE

The total hose weight per foot was assumed to be 0.5 lb (2.2 N) per foot. The results of initial calculations appear below for a thruster with twelve cylinder pads (1.5 x 8 in.) [3.8 x 20.3 cm]

MINIMUM REQUIRED SHEAR RESISTANCE TO PULL THRUSTER CABLES

	Tunnel Length ft (m)				
	1000 (305)	2000 (610)	3000 (915)	4000 (1220)	5000 (1525)
Friction Force Component From Hose Weight lbf (N)	360 (1602)	720 (3204)	1080 (4806)	1440 (6408)	1800 (8010)
Minimum Required Shear Resistance tsf (N/m^2)	0.18 (17.2×10^3)	0.36 (34.5×10^3)	0.54 (51.7×10^3)	0.72 (70.0×10^3)	0.89 (85.3×10^3)

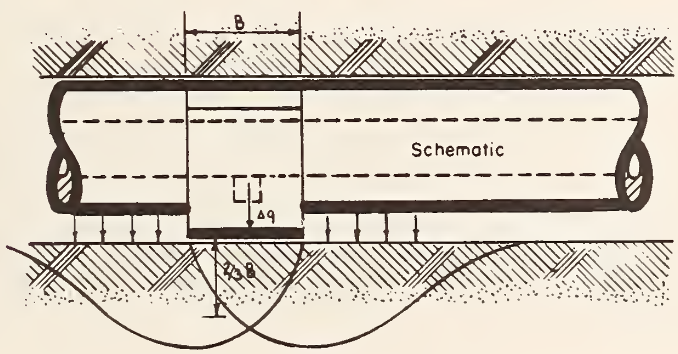
G.5 ANCHORING PRESSURE REQUIREMENTS FOR THE ANCHOR PADS AND DEFLECTION SHOE

The anchoring-pressure calculation accounts for two different soil types (cohesionless-sand; cohesive-clay), therefore, two different bearing capacity formulae will be applied with the following assumptions:

1) The DRILCO Thrust Applicator anchor pad or the CONOCO deflection shoe contact surface is assumed to be flat (for ease of calculations) with a minimum dimension equal to the length of the chord over the arc of the original shoe.

2) The bentonite filter cake that is present in the drill hole sides, as a result of using a mud slurry, will be displaced by the anchor pad/deflection shoe upon contact so that the pad/shoe bears directly on the sand.

3) The drilling fluid pressure will increase the bearing capacity for the anchor pads as shown in Figure G.4. This increase will not occur for the deflection shoe because the drilling fluid pressure acts on both sides of the shoe as shown in Figure D.14.



For Clay: $\Delta q_{ult} = N_c S_u + \Delta P_a$

For Sand: $\Delta q_{ult} = \frac{1}{2} S_\gamma \gamma B N_\gamma + \Delta P_a$

Δq = Applied Stress

ΔP_a = Annular Drill Fluid Pressure Minus Water Pressure

S_γ = Shape Factor (Vesic, 1973)

N_c = Bearing Capacity Factor (Skempton, 1973)

N_γ = Bearing Capacity Factor (Vesic, 1973)

FIGURE G.4 ASSUMED FAILURE MECHANISMS FOR ANCHOR

4) The load on the anchor pad is uniform and normal to the drill hole wall.

5) A punching bearing capacity failure will occur when the maximum contact stress exceeds the bearing capacity. The maximum contact stress is that which is available over the anchor pad at maximum hydraulic pressure without causing the anchor pad to rupture.

First, the contact stress for a 5 3/4 in. (14.6 cm) O.D. thrust applicator and for the deflection shoe are calculated. This thruster is modeled because the exact maximum hydraulic pressure possible without membrane rupture is known. For mechanical details see Appendix D. However, a modification would have to be made to the external dimensions of the anchor pad (contact area) for soft ground application. An extension pad, with contact dimensions 1.5 x 8 in. (3.8 x 20.3 cm), can be attached to the thrust applicator pad. Then the normal contact stress, Δq , would be the ratio of the internal hydraulic piston area to the external pad area, times the hydraulic pressure applied over the internal area.

$$\Delta q = \Delta P_H \left(\frac{A_I}{A_C}\right)$$

P_H = change in hydraulic pressure (psi) necessary to anchor

A_I = pad area in contact with the hydraulic fluid

A_C = contact area of anchor pad with drill hole wall

The results of these contact stress calculations are plotted in Figure G.5.

Next the deflection shoe and anchor pad anchoring pressures were calculated for MPS's with 7 in. hole diameters operating in soft and stiff clay and loose and dense sand. The results of the computations are presented in Table G.4.

TABLE G.4: MAXIMUM ANCHORING PRESSURES (Δq_{max}) FOR ANCHOR PADS AND DEFLECTION SHOE

Soil	Device	S_u (tsf) or γ_b (pcf)	q_{ult} (tsf) Drill Hole Length ft 1000 (305 m)	5000 (1525 m)	
Clay	Thruster	S_u = 0.25	2.35	4.65	
		= 2.0	11.78	14.08	
	Deflection	= 0.25	1.47	1.47	
	Shoe	= 2.0	11.74	11.74	
Sand	Thruster	γ_b = 47.6	1.05	3.34	
		= 72.6	1.07	3.17	
	Deflection	= 47.6	0.05	0.09	
	Shoe	= 72.6	0.15	0.15	
			1.0	3.3	ΔPa*

* See Figure F.3

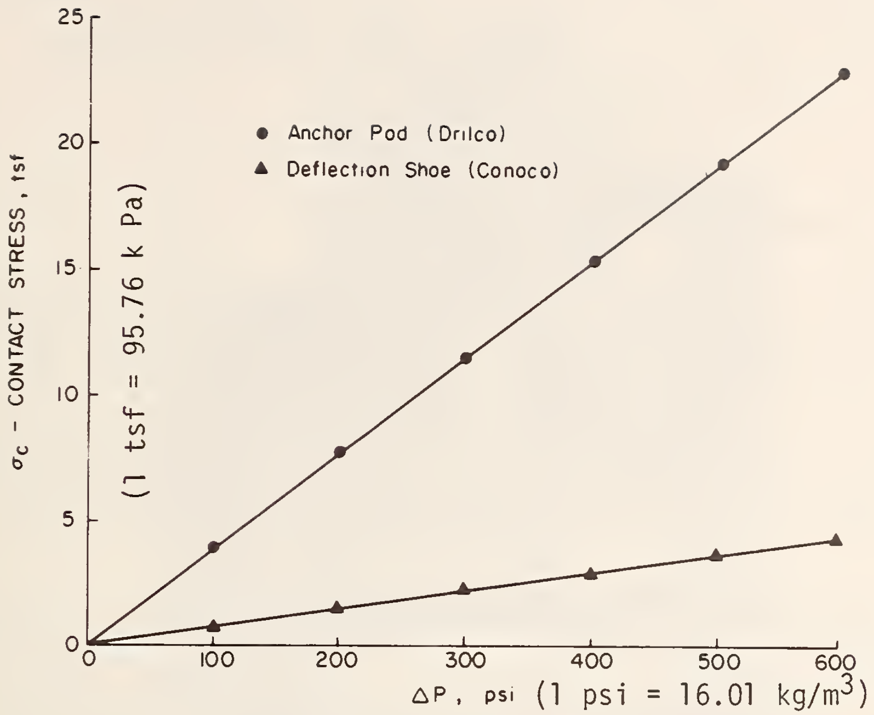


FIGURE G.5 CONTACT STRESS VS. CHANGE IN HYDRAULIC PRESSURE

Several facets from Table G.4 require further discussion. Foremost is the effect of the excess annular fluid pressure ΔP_a. Δq_{max} for the anchor pads is greater than that for the deflection shoe by ΔP_a because of geometry differences. Figure D.14 shows that the deflection shoe is open to the pressurized annulus while the anchor extension mechanism is not. Therefore, the incremental hydraulic pressure necessary to fail the anchor pad is greater because during extension it must overcome both ΔP_a and the surface bearing capacity of the soil.

Secondly, if pumping is stopped, P_a will decrease to approximately the difference between slurry and water unit weights times the depth, $(\gamma_f - \gamma_w)z$, which will be minimal. Therefore, Δq_{max} will be small for shallow sections of the hole with no pumping. ΔP_a is also low during initial entry because of low head losses.

Thirdly, the maximum anchoring pressures for sand are low. These low pressures result from the assumptions of no confinement and a flat rather than curved surface. Therefore, the calculated anchoring pressures are somewhat conservative.

From the above discussion, it is obvious that the anchor and deflection shoe extension pressures will have to be controllable so as not to exceed the bearing capacity of the hole. If the bearing capacity is exceeded, the available anchor thrust will be reduced. However, an environment which demands rapdily changing contact stresses, Δq_{max} requires complex downhole valving. For the sensitivity required,

a downhole pressure regulator will be needed to control the contact stress. CONOCO's downhole valving system has a single pressure setting. It has only been tested in coal where bearing capacity conditions do not change rapidly.

G.6 SOIL FRICTION AND THE MANDREL MPS

CASE STUDY--MAXIMUM FRICTION

The data for this case study on the effects of in-hole frictional resistance were taken from the Cerritos Channel crossing made by Titan Contractors (See Appendix N). A 1 3/4 in. (4.5 cm) Dyna-Drill was used with 2 1/8 in. (5.4 cm) O.D. BQ drill pipe and a 2 3/4 in. (7 cm) diameter drag bit. The initial entry angle and sketch of the drill rig are shown in Figure G.6b. The one exploratory boring taken showed a soil profile of a layered system of sand and silty-sand down to an approximate depth of 85 ft (26 m) below the original ground surface.

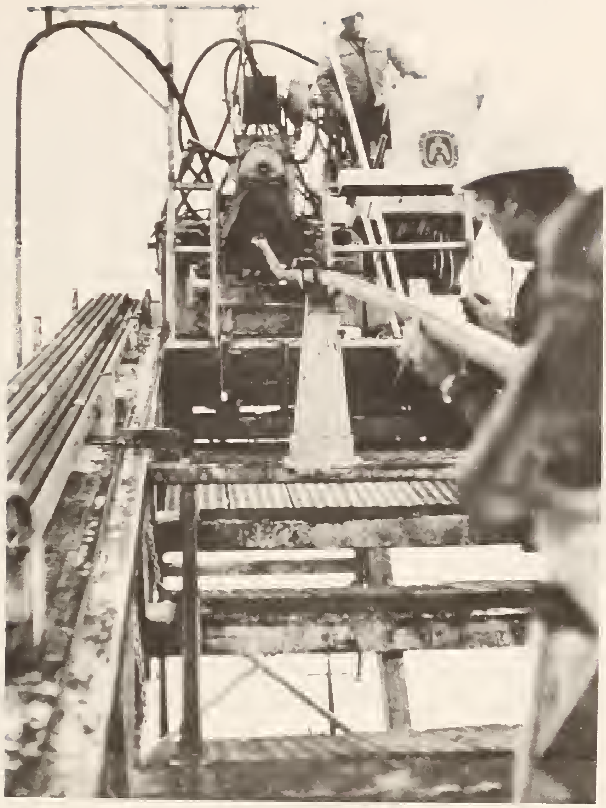
When the drill hole had reached a length of about 300 ft (91.5 m), as shown in Figure G.6a, the BQ rod buckled on the drill rig as the carriage was applying a normal force. At this point the average depth was 65 ft (19.8 m). In order to calculate the approximate applied force at the time of buckling, the drill pipe will be assumed to be a slender column which is fixed at the rotary motor and pin-connected at the vice clamp as illustrated in Figure G.6b. The dotted line in Figure G.6b shows an exaggerated form of the deflected BQ rod. This deflected shape can also be seen in the picture in Figure G.6a.

Applying Euler's slender column buckling criteria, the critical normal force was calculated as 2.68 Kips (11,926 N). The unsupported length was 25 ft (7.6 m); the second buckling shape applied.

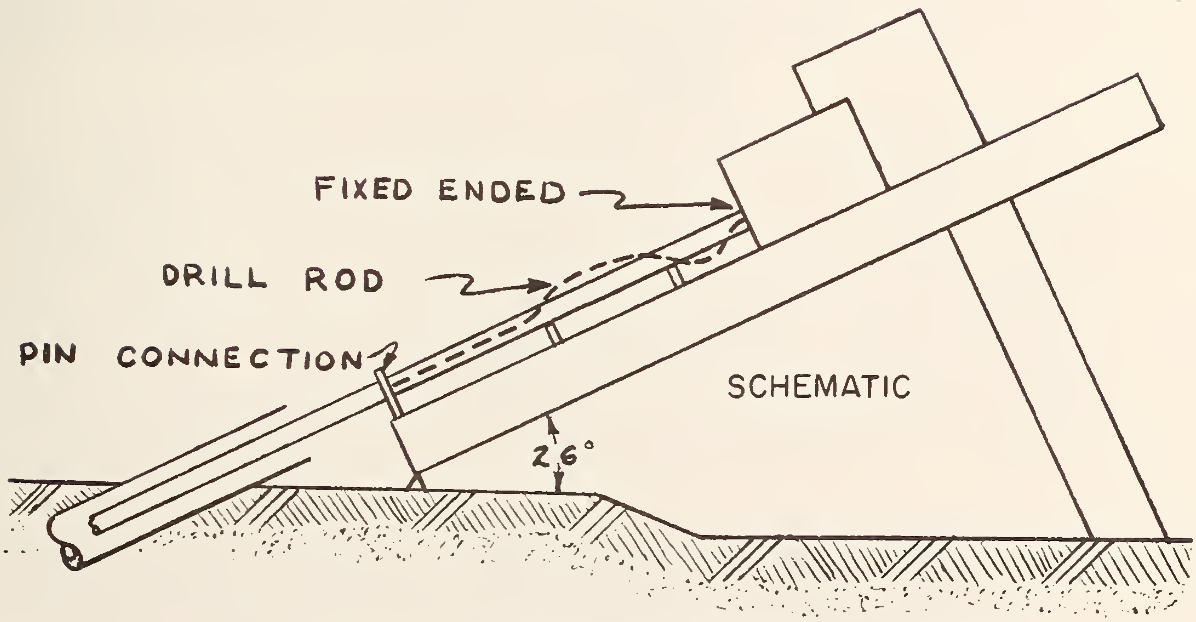
The frictional resistance of the BQ drill pipe is calculated with a relationship similar to the skin resistance along a pile. The total contact area is $A_c = \pi dL$ and the frictional resistance is 10.72 lb/ft (156.4 N/m). This is the assumed skin friction on the drill motor and drill pipe in silty sand conditions below the water table when the hole collapses.

MINIMUM FRICTION

For a non-collapsed hole which is horizontally oriented, the resistance will be a function of the buoyant weight of the BQ drill string (3.83 lb/ft) (55.9 N/m). A preliminary calculation of the frictional force caused by dragging a pipe over sand reveals that this frictional resistance is approximately 2.21 lb/lf (32.2 N/m). With $\phi = 30^{\circ}$ if a special BQ rod could be manufactured so that it were neutrally buoyant, then this resisting force could be reduced even further.



a) DEFLECTED BQ ROD



b) TITAN CONTRACTOR'S DRILL CARRIAGE

FIGURE G.6 OUT-HOLE BUCKLING

G.7 SOIL FRICTION AND THE THRUSTER MPS

MAXIMUM

The worst frictional condition for a thrust applicator occurs when the drill hole behind the thruster collapses at a depth of 500 ft (153 m). Certainly the resistance per foot of cable will be in excess of that back calculated from the Long Beach experience in G.6. A preliminary estimate of friction due to collapse at depth was made with the following assumptions:

(1) The radial stress against the thruster hose is illustrated in Figure G.7. The value of $\bar{\sigma}_r = .2\bar{\sigma}_{vo}$ is derived from measurements made by Hoeg (1965) on yielding tunnel liners; (2) In order to pull the thruster hose, the sand must be failed in shear according to the Mohr-Coulomb criteria ($\tau_{ff} = \bar{\sigma}_{vo}\tan\phi$); (3) The sand is completely saturated; (4) The soil properties are: γ = 120 pcf, γ_b = 57.6 pcf, $\phi = 35°$.

Collapse friction could be as high as 2000 lb/ft (29 180 N/m). Obviously with existing thrusters (which can develop maximum thrusts of 10,000 lbs (44.5×10^3 N) under optimal conditions) hole collapse cannot be tolerated.

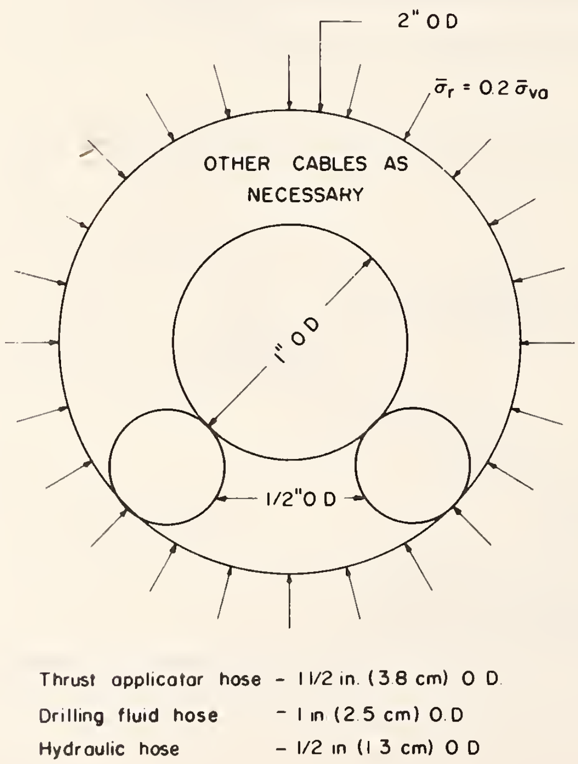


FIGURE G.7 RADIAL STRESSES APPLIED TO THE THRUSTER HOSE

MINIMUM

The minimum cable friction (drag) will be developed by the slurry flowing past the neutrally buoyant cable. Since a special cable will probably be manufactured for this system, a neutrally buoyant design should not be a large extra cost factor. The pseudo-plastic fluid drag has been calculated in Appendix F. The annular flow was found to be laminar and to exert a drag force of 0.04 lb/ft (.62 N/m) of cable. This friction force is the lowest of all the possibilities, but is dependent upon neutral buoyancy of the cable.

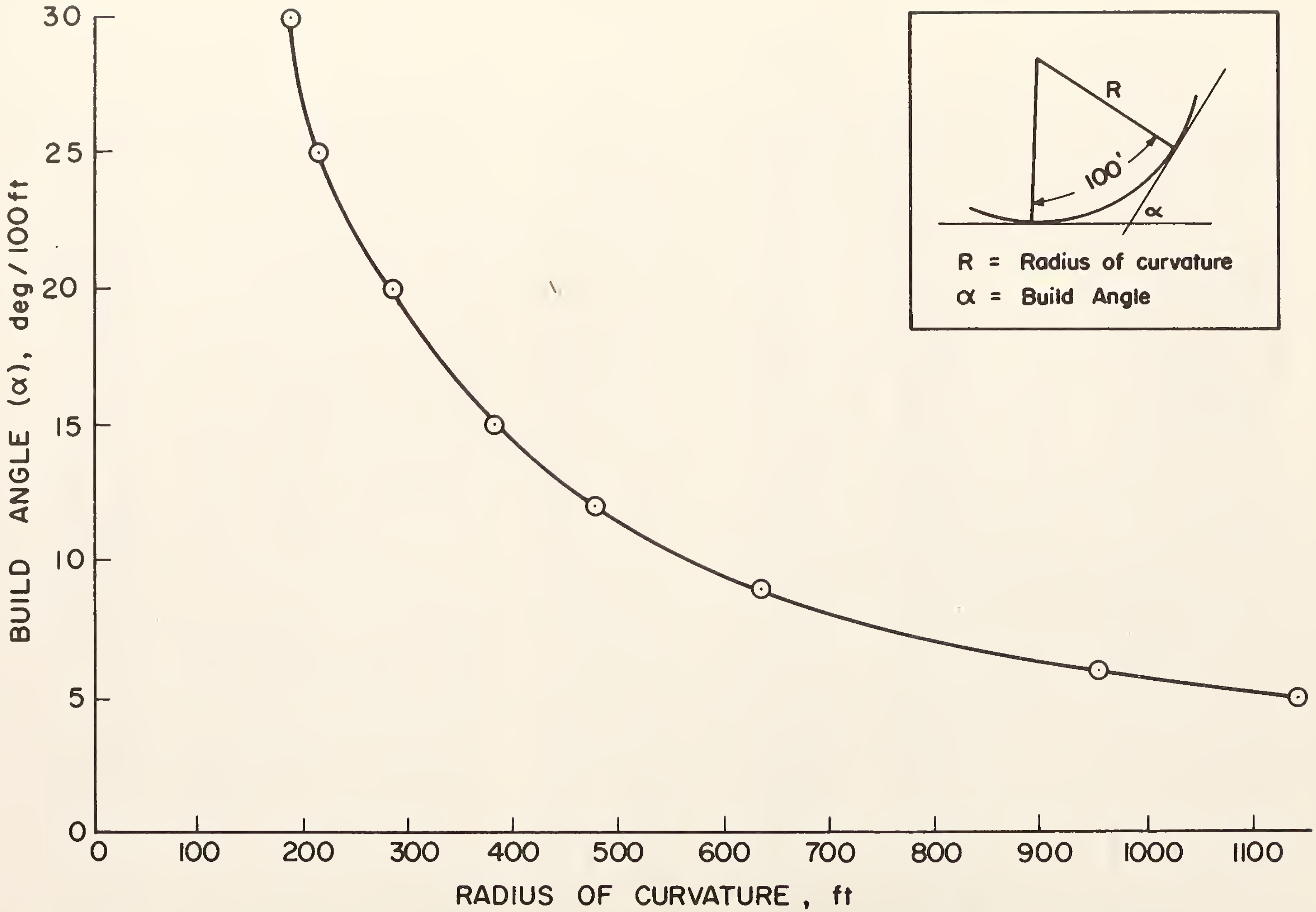
G.8 MINIMUM RADII OF CURVATURE

There are at least three reasons for measuring the radius of curvature of the drill path. First, an equipment limitation factor can be defined for the mandrel and thruster MPS based on the minimum permissible radius of curvature of the drill path. Secondly, these equipment limitations, when combined with the calculation of spiral path adjustments, define minimum detection distance for obstacle avoidance. Finally, with knowledge of the radius of curvature the maximum depth required for horizontal path orientation, or conversely, the minimum horizontal distance required for horizontal orientation can be calculated as a function of the entry angle.

This section will deal with these three applications of the radius of curvature calculations. Radius of curvature is defined and translated to build angle per 100 ft (30.5 m) of travel (the "oil patch" approach to radius of curvature). Once these basic definitions have been established, the three applications of the radius of curvature will be discussed in the above mentioned order.

In Figure G.8 , the method and terminology associated with calculating the radius of curvature is illustrated for small α's or large radii of curvature. The relationship between the radius of curvature, the horizontal displacement, depth, and entry angle is shown in Figure G.14. Both the depth and horizontal distance are a function of the entry angle for constant radius of curvature (circular) drill paths. The term "build angle" is basic to both of the above geometrical definitions. Build angle is actually an angular rate of change measured over a specified distance of the drill path. Traditionally this rate of change has been expressed in degrees of change per 100 ft (30.5 m) of drill path. Later in this section the effect of reducing the length between surveys will be discussed.

Figure G.8, translating build angles to radii of curvature, was derived from the geometry illustrated in G.8. As can be seen from the graph, when the rate of angular change increases, the radius of curvature for the drill path decreases.



(1 ft. = 0.305 m)

FIGURE G.8 RADIUS OF CURVATURE VS. BUILD ANGLE

EQUIPMENT LIMITATIONS

Upperbound equipment limitations have been established for the mandrel and thruster MPS and are based on the minimum radius of curvature the equipment can negotiate without inducing any internal bending moment or additional side friction from lateral loads. This minimum arc is described by the three contact points: A, B, and C in Figure G.9.

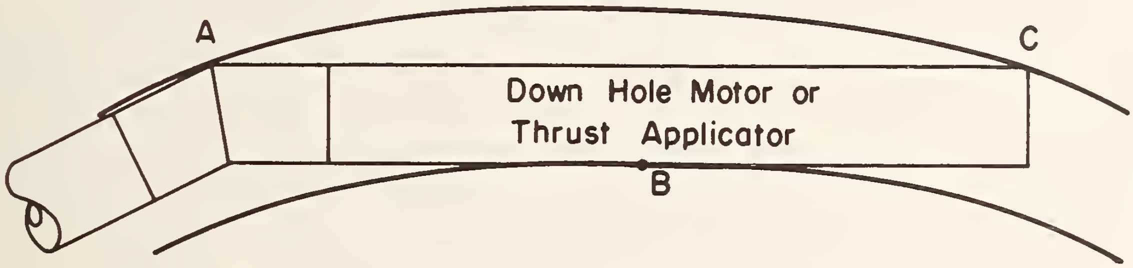


FIGURE G.9 EQUIPMENT RADIUS OF CURVATURE LIMITATIONS

This definition for the minimum radius of curvature is true for both MPS's and since both MPS's are of similar length, the minimum value for the build angle is 5°/100 ft (5°/31 m) which yields a radius of curvature equal to 1145 ft (350 m).

The lower bound equipment limitations for the two MPS's were not theoretically calculated because of the many unknwon variations which affect the maximum allowable bending moment for the equipment. Instead the minimum radius of curvature if the MPS were pushed to its limits for a short period of time was established through field experience with the two systems. Titan Contractors have surveyed a mandrel MPS (1 3/4 in. O.D. Dyna-Drill) drill hole and measured an arc which correlated to a build angle of 26°/100 ft (26°/31 m) (Emery, 1975).

This is a maximum singular angular rate of change and is not an acceptable long term operating condition. For the thruster system, the maximum build angles experienced by CONOCO have been in a range from 13^{o}/100 ft (13^{o}/31 m) to 15^{o}/100 ft (15^{o}/31 m), which were measured during a field test in soft coal using the DRILCO thrust applicator (Edmond, 1975).

MINIMUM DETECTION DISTANCE FOR OBSTACLE AVOIDANCE

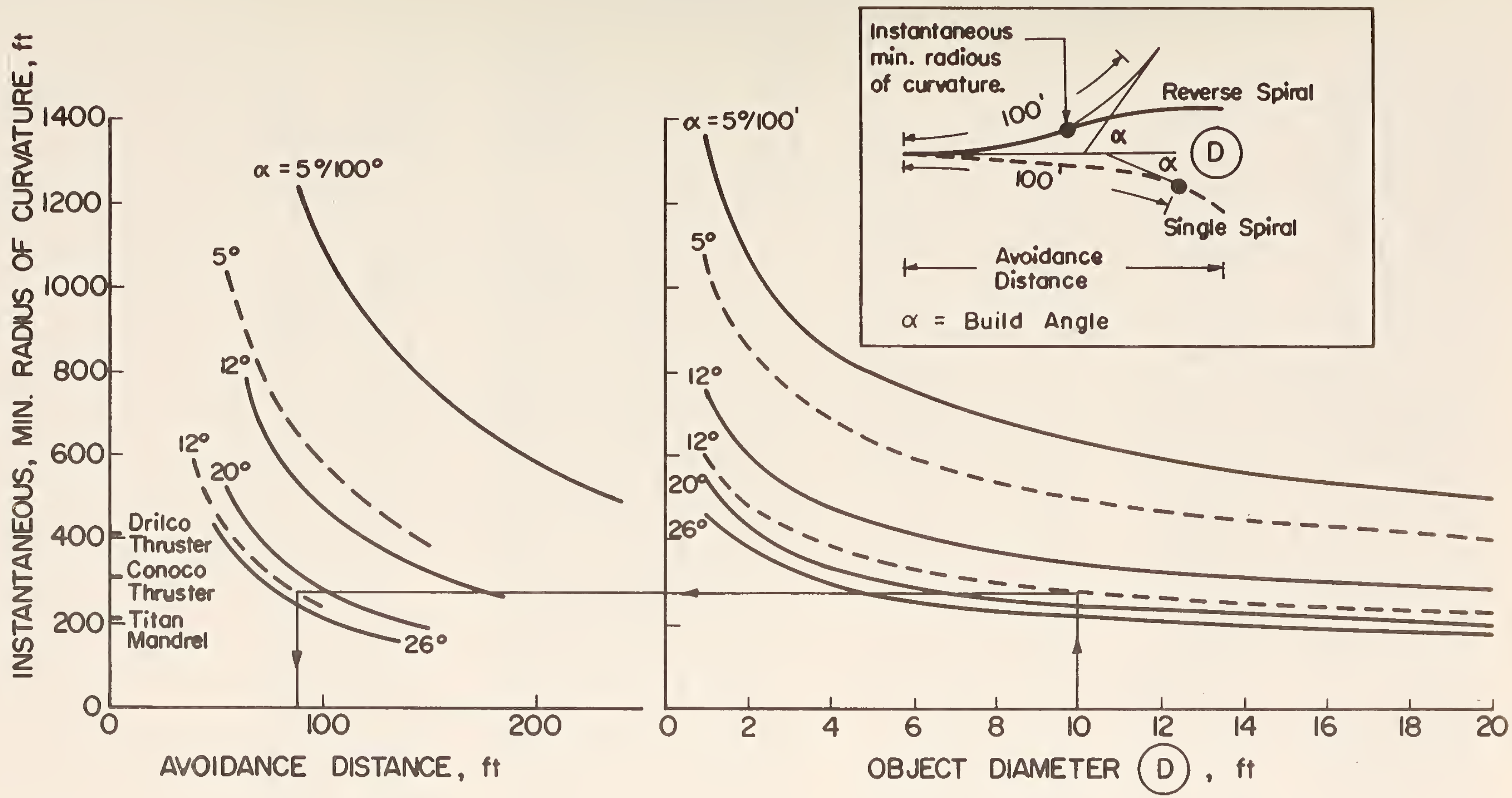
One of the major objectives of developing a highly maneuverable penetration system is object avoidance. To evaluate the ability of the drilling equipment to avoid an object, a model of the path had to be selected. A single spiral and reverse spiral, shown in the box in Figure G.10, were chosen over a circular path.

The spirals were selected in place of circular paths because of their ability to represent crabbing, a phenomenon believed to be associated with drilling in soft ground. Crabbing occurs when a directional change is initiated with the MPS and the MPS does not immediately respond in changing direction along a circular path. But instead, it progressively deviates from its original drill path by decreasing the radius of curvature as it progresses. The rate of the progressive change of direction is believed to be a function of compaction (in loose sands) which tends to increase the sand's bearing capacity and hence its ability to resist the applied skewed load. Since no drill hole in soft ground has been surveyed in small enough increments to establish the exact trajectory, the existence of crabbing is hypothetical but definitely possible. The exact soil behavior causing direction change needs further investigation.

Both the single and reverse spiral were selected to represent two different avoidance situations. The single spiral represents the case where object avoidance is the only course desired without any consideration for returning to the original direction of drilling. The reverse spiral considers returning to the original direction of the drill path.

Avoidance distances for several sized objects have been calculated as a function of a specific build angle. The build angle for these calculations is defined as the angle between a tangent to the spiral at a particular point on the spiral and a tangent to the original drill path as shown in Figure G.10. The distance to the point where α is measured has been chosen as 100 ft (31 m) for both reverse and single spirals.

The results of the calculations are plotted in Figure G.10. To find the minimum avoidance distance for a particular type of equipment first go into the right hand abcissa with a predetermined build angle and a diameter of object to be avoided, and find the radius of curvature for either a single or reverse spiral drill path. Then move across to the left hand graph with the same radius of curvature and build angle and find the distance required to avoid this particular size object.



(1 ft. = 0.305 m)

FIGURE G.10 AVOIDANCE DISTANCE WITH SPIRAL PATH ASSUMPTIONS

Spiral path assumptions are the most realistic given the mechanism controlling direction change. Since no detailed path surveys are available, it is still possible that paths might be circular. The circular path is illustrated in Figure G.11 along with the necessary observation distances necessary for object avoidance under circular path assumptions. This circular path assumption is certainly optimistic and represents an upper bound for equipment performance.

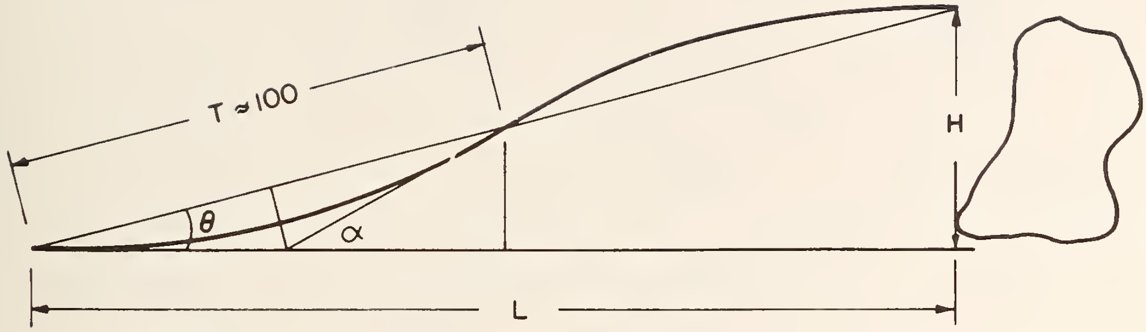
With a build angle, α, of 9° the minimum avoidance distances for a 5 ft (1.5 m) object are 63 ft (19 m) and 110 ft (34 m) for the double circle and double spiral paths. This difference is considerable but reflects the lack of precise path measurements in soil. These path measurements should be made.

PENETRATION DISTANCES AND DEPTHS NECESSARY TO ACHIEVE HORIZONTALITY

Two factors affect the horizontal distance and vertical depth at which an MPS will reach a horizontal plane: the entry angle and radius of curvature of the drill path. In Figure G.12 a vertical entry angle has been chosen to display the variation in depth and horizontal distance as the build angle is changed. This graph shows the optimal continuous operating range for both the mandrel and thruster MPS.

Drill paths in Figure G.12 are drawn at 100 ft (31 m) increments between angle change points. The difference between the calculated drill paths for angle change rates measured every 100 ft (31 m), which is the standard interval, and those measured every 30 ft (9.2 m) are shown in Figure G.13. The calculated drill path that is surveyed and plotted every 30 ft (9.2 m) falls below the one measured and plotted every 100 ft (31 m) while the actual build angle for the former drill path is $10.5^{\circ}/100$ ft instead of the expected $12^{\circ}/100$ ft. The discrepancy is the result of assuming the chord and arc length to be equal as discussed in the subsection "Drill Path Radius of Curvature." Therefore, by decreasing the course length between measurement points, a more accurate representation of the drill path and capabilities of the MPS are represented.

A plot of the mathematical relationship between constant radii of curvature, horizontal distance, depth, and entry angle is illustrated in Figure G.14. By increasing the entry angle, δ, the depth required to reach a horizontal plane decreases but the horizontal distance to that point increases for a constant radius of curvature.



α = Build angle / 100 ft

T = Travel distance

L = Sighting distance = $H / \tan(\alpha/2)$

	α	L, ft (m)			
		H = 5		H = 10	
	5°	114	(35)	228	(70)
Continuous Optimum	9°	63	(19)	126	(38)
	15°	38	(12)	76	(24)
	20°	28	(8.5)	56	(17)
Kink	25°	22	(6.7)	44	(13)

FIGURE G.11 AVOIDANCE DISTANCE WITH CIRCULAR PATH ASSUMPTIONS

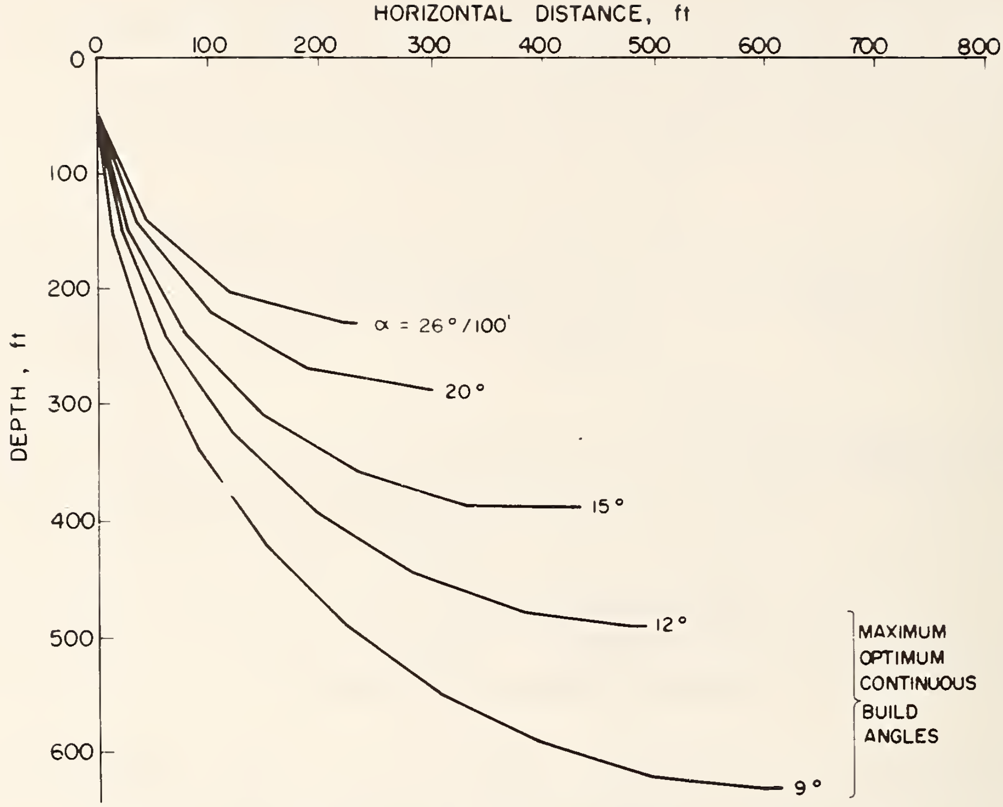
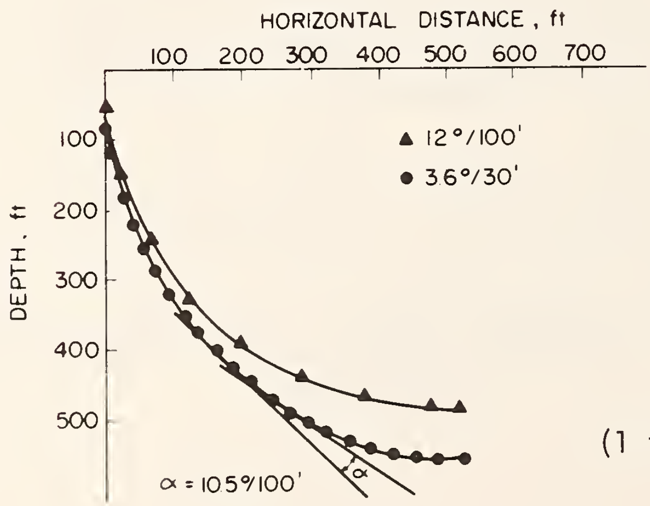


FIGURE G.12 HORIZONTAL DISTANCE VS. DEPTH FOR VARIOUS BUILD ANGLES



(1 ft. = 0.305 m)

FIGURE G.13 BUILD ANGLE COMPARISON

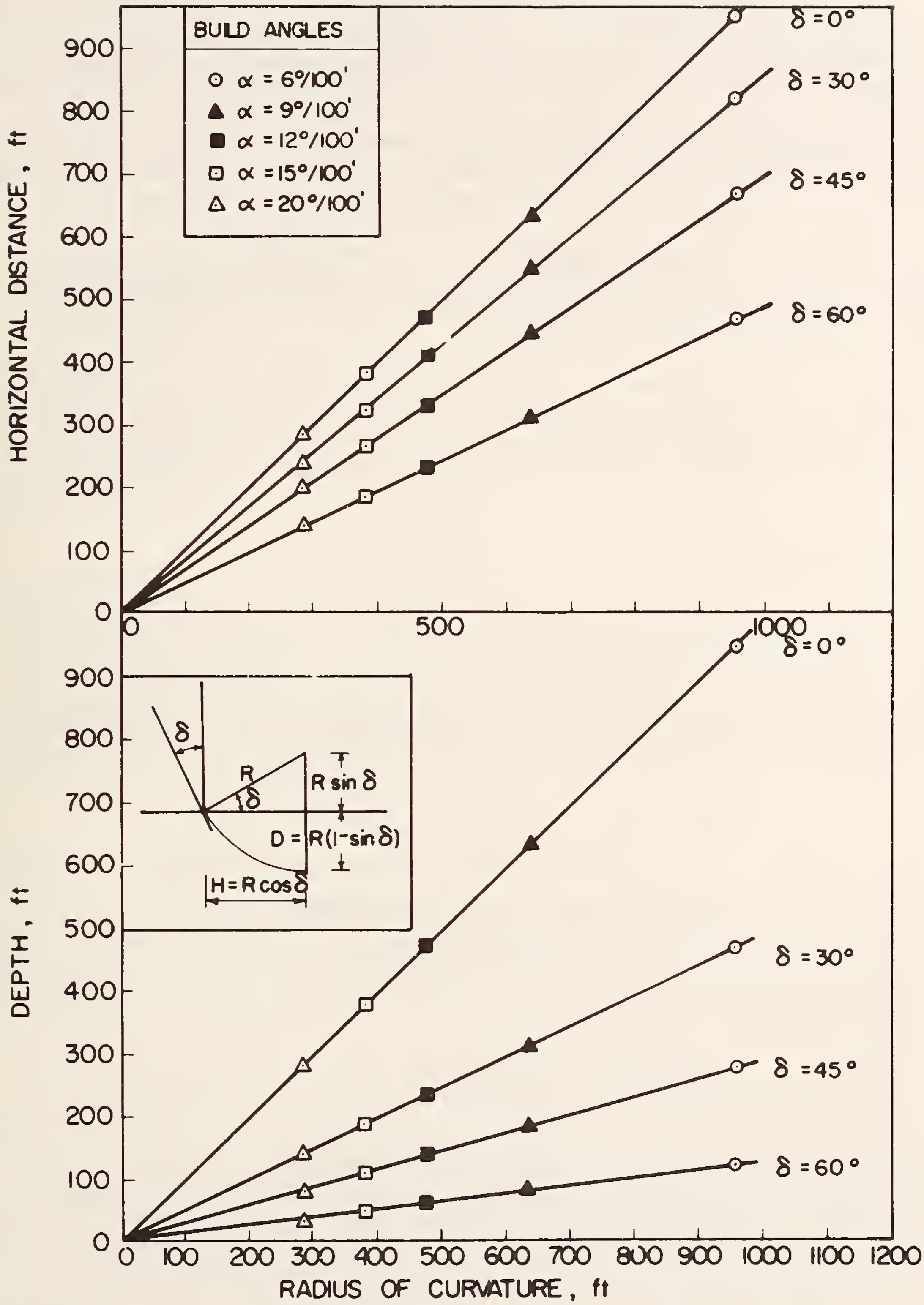


FIGURE G.14 RADIUS OF CURVATURE VS. HORIZONTAL DISTANCE/ DEPTH FOR VARIOUS ENTRY ANGLES

(1 ft. = 0.305 m)

G.9 DIMENSIONLESS ANALYSIS CALCULATIONS

No method of comparing divergent drilling systems exists. The lack of systematic comparison is due to the difficulty of (1) developing a set of dimensionless parameters which describe performance of highly variable mechanical systems in variable geologies, and (2) obtaining actual downhole performance data. This section describes the selection and application of comparative parameters tempered by the dual requirement of applicability in a variety of geological conditions and simple practicality.

Of the four parameters presented, three are dimensionless while the fourth has units. The dimensionless ratios are the shearing parameter, jetting parameter, and the fluid system parameter. The dimensional parameter is the drill motor parameter.

Each of these parameters will be presented separately along with the logic of their derivation and optimal values. The four systems described in Chapter 2, Section 4 are then evaluated with the parameters. The reasons for evaluating these particular four systems are explained in Chapter 4.

SHEARING PARAMETER

The shearing parameter has been developed to indicate some measure of the torque required to shear the soil (at the outer edge of the bit face) in relation to the torque that is available from a particular motor with a specific size drill bit. The torque required to shear the soil was derived from the cylindrical torque equation with the maximum torque resulting at the bit-drill hole wall interface:

$$T = \frac{\tau_{max}}{r} J$$

$\tau_{max} = S_u$ = undrained shear strength of the soil

r = radius at the bit-soil interface

$J = \frac{\pi d^4}{32}$ = polar moment of inertia

The resulting parameter is:

$$SP = \frac{\frac{S_u(J)}{r}}{T} = \frac{S_u \frac{\pi d^3}{16}}{T}$$

Two different undrained shear strengths were adopted for these calculations. An S_u = 0.25 tsf (soft clay) is the best condition for shearing because of its low resistive shear strength while conversely, an S_u = 2.0 tsf (stiff clay) is the worst soft ground condition with respect to shearing at the outer edge of a bit face.

The criteria established to evaluate the shearing parameter is that if the ratio is less than one, the drill motor and bit will be able to

shear the soil from a dead start. A value greater than one does not mean that the motor/bit combination will not be able to drill in that specific soil, but instead that if the drilling operation depended solely on the shear ability of the system at the soil-bit interface, then the system could not drill.

The various values for the shearing parameter for each system considered in the final equipment design are given below.

Drill System	System Torque (ft/lb)	Shearing Parameter $S_u = 500$ psf	Shearing Parameter $S_u = 4000$ psf
2 3/8 in. O.D. Dyna-Drill 4 1/2 in. hole	30	0.173	1.38
6 1/2 in. O.D. Dyna-Drill 12 in. hole	467	0.21	1.68
5 in. O.D. Hydraulic Motor 7 in. hole	175	0.111	0.89
3 11/16 in. O.D. Electric Motor 7 in. hole	175 @ 150 RPM	0.111	0.89

(1 in. = 2.54 m; (ft. - lb. = 1.356 m-N)

JETTING PARAMETER

One of the most important considerations in selecting a drilling system to bore a hole in soft ground is the erosive potential of the drill fluid as it jets out of the bit orifice. Some degree of jetting is desirable in order to increase the efficiency of the drill bit; however, an excess of jetting will create a large cavity in front of the bit.

The jetting parameter (JP) represents the velocity of a fluid to cause erosion (Ve) of a particular soil compared to the jet stream velocity emitting from the bit orifice ($GPM/A_{B.O.}$), or JP $= V_e$ (448.8)/ $GPM/A_{B.O.}$ The erosion velocity was determined for water and not drilling mud since no data were available for mud slurry. At the same velocity flow of water is more turbulent than flow of slurry because of the slurry's higher viscosity. Therefore, the erosion velocity reported in the literature is probably lower than it would be for a drilling mud. JP assumes the jet flows directly from the orifice to the borehole face. This is an unconservative assumption, since the flow pattern is in reality a vortex and the vortex flow would increase the erosion effect at the bit face.

The erosion velocity data were found for a sand-gravel soil and a clay soil. The value adopted for the erosion of sand was taken from Hjulström (1935). The erosion velocity is 0.65 ft/sec (20 cm/sec) for a turbulently flowing stream with 0.5 mm diameter particle. A value for the erosion velocity in clay was taken from Graf (1971) and equal to 4 ft/sec (1.2 m/sec).

If the velocity required for erosion is greater than the bit orifice velocity, JP > 1 and no erosion at the bit face occurs. Therefore, the smaller JP is, the more erosion in front of the bit.

In some cases impact erosion can be helpful in directional guidance When coupled with variable rates of advance, therefore, there is no recognized criteria for optimum JP's. However, JP can be used to evaluate the relative effects of jetting between various bit/motor/flow rate combintaions for different soil environments.

The following presents the results of the jetting parameter for the various bit sizes considered in the equipment designs. The diamond bit is not included because it does not have orifices but instead has fluid passages. Therefore the erosion mechanism will differ.

Bit Type	O.D. (in.)	GPM	Orifice Area (ft^2)	JP Sand	JP Clay
Tricone	7	30	0.0009	0.009	0.063
	12	325	0.0021	0.002	0.014
Drag	4 1/2	25	0.0005	0.006	0.045

(1 in. = 2.54 cm; $ft.^2 = 0.09\ m^2$)

DRILL MOTOR PARAMETER

The two previously discussed parameters have been dimensionless and have dealt with the geological aspects of drilling in soft ground. The drill motor parameter describes the equipment characteristics of each drilling motor. The parameter is not dimensionless, and compares the horsepower output with respect to the volume of the motor to the torque output. Therefore, the drill motor parameter (DMP) = H.P. (550)/ Vol/Torque.

A more meaningful parameter for evaluating different motors in various soil conditions has been developed by Cook and Harvey (1974). They evaluated the efficiency of excavating in rock in terms of the specific energy of rockbreaking and the specific power, that is the power that can be delivered to a unit area of the working face. The specific energy is the energy consumed (per unit volume) to break the rock and is a function of the type and condition of the rock, the strength, and the size of broken particles. This type of comparison would have been adopted except the specific energies of various soils are unknown.

Smaller DMP's signify more efficient use of the volume of the motor for the rated design power and torque outputs. The following lists the results of DMP calculations for the four proposed equipment designs.

	H.P.	Volume (ft^3)	Torque (ft/lb)	DMP ($1/ft^3$ - sec)
2 3/8 in O.D. Dyna-Drill	6	0.215	30	511.60
6 1/2 in. O.D. Dyna-Drill	28	4.52	467	7.30
5 in. O.D. Hydraulic Motor	10	0.79	175	39.78
3 11/16 in. O.D. Electric Motor & Gear Box @ 250 RPM	5	0.348	175	45.20

(1 in. = 2.54 cm; $ft.^3$ = .03 m^3, ft. - lb. = 1.356 m-N)

FLUID SYSTEM PARAMETER

The final parameter relates the annular pressure in the drill hole at the bit as represented by the equivalent circulating density (ECD) to the hydraulic fracture gradient (Fg) or fracture susceptibility of the formation being drilled. The fluid system parameter is ECD/Fg. The ECD should not be greater than the hydraulic fracture gradient. If the ECD is greater, then loss of circulation occurs and the drilling system becomes stuck in the hole.

The following lists all of the values of ECD/Fg for the various systems considered. Details of this calculation are contained in Appendix F in Sections F.3 and F.6. This table contains ratios for ECD <u>calculated</u> <u>with</u> <u>no</u> fines to demonstrate the relative efficiency of the four systems.

Motor Type	ECD pcf 1000 ft pentration		Fg pcf		ECD/Fg			
			Clay	Sand	Clay		Sand	
	Depth (ft)				Depth (ft)			
	100	500			100	500	100	500
$2\frac{3}{8}$ in O.D. Dyna-Drill	108	75	100	96	1.08	.75	1.12	.78
$6\frac{1}{2}$ in O.D. Dyna-Drill	76	68	100	96	.76	.71	.73	.68
5 in O.D. Hydr. Motor	76	68	100	96	.76	.71	.73	.68
The electric motor was not considered because flow volumes are unrelated to motor efficiency.								

(1 in. = 2.54 cm; 1 ft. = 0.305 m; pcf = 16.01 kg/m^3)

APPENDIX H

STABILITY OF HORIZONTAL BOREHOLES

H.1 INTRODUCTION

After initial background information was gathered and the possible methodologies for soft ground exploration were outlined, it became apparent that borehole stability and disturbance would control the system design for the following three reasons.

1. The borehole walls must be kept from caving to decrease frictional forces on the excavation equipment and allow efficient removal of cuttings.

2. Size and compatibility of the exploration devices with the excavation system would rule out or demand redesign for simultaneous operation. Stopping the excavation to allow exploration would cause substantial increases in the borehole excavation costs. These two major difficulties could be overcome if stability of the borehole was ensured. Thus, separate "follower packages" for exploration could be pulled through the excavated hole after removal of the excavation equipment.

3. Disturbance of the soil around horizontal boreholes could lead to wrong or misleading conclusions concerning the soil parameters if they were measured in such a disturbed zone.

Section H.2 of this appendix describes the stress in situ below a horizontal ground surface. When a borehole is excavated in the ground, the stress field will change in the vicinity of the borehole. Various analytical solutions for this stress change are given in section H.3. Section H.4 describes the interaction between the drilling fluid and the ground surrounding the borehole. Borehole stability as related to the change in state or stress with time are discussed in Section H.5.

H.2 EARTH PRESSURE AT REST

DRY SOILS

The term "earth pressure at rest" denotes the pressure (or stress) distribution with depth existing in situ before any disturbance. The vertical stress, σ_V, acts in the vertical direction, the horizontal stress, σ_H, in the horizontal direction. The vertical stress is normally computed as the sum of the gravity stress above the point in question. According to Marr (1974), earth pressure measurements have always yielded values of vertical stresses smaller than the gravity

stress. It will, however, be assumed that the vertical stress is equal to the sum of the gravity stresses.

The horizontal stress cannot readily be computed. Measurements and empirical correlations are employed to find its magnitude (See Marr, 1974, for extensive treatment). The horizontal stress is usually expressed as a constant times the vertical stress, and in soil assumed equal in all directions:

$$\sigma_H = K_o \sigma_V$$

This constant, K_o, is called the coefficient of earth pressure at rest (or lateral stress ratio at rest). Its magnitude in loose sediments can vary from 0.3 to 2 and more, with an average of 0.5. The higher values of K_o are caused by overconsolidation (O.C.), i.e. the effective soil stresses were higher in the past than today. Overconsolidated soil is often found in the upper 15-30 ft (5-10 m) of the subsurface profile, and less frequently at greater depth.

For normally consolidated (N.C.) soils, the following semi-empirical formula is often employed to calculate K_o:

$$K_o = 1 - \sin \phi$$

where: ϕ = soil friction angle.

SATURATED SOILS

If the voids between the soil particles are filled with water instead of gas (air), the total soil weight will increase. The surface where the pore water pressure is zero (or where the water level in a well would be), is called the ground water table (GWT).

The soil stress below the GWT can either be expressed as total stress (σ) or as effective stress ($\bar{\sigma}$), where the effect of buoyancy (unit weight of water) has been subtracted from the total soil weight before computing the stress. The general expression of this relationship is:

$$\bar{\sigma} = \sigma - u$$

where: u = pore water pressure.

K_o for water (and any solid without shear strength) is one. The horizontal stress in soils below the GWT will therefore be:

$$\sigma_H = \bar{\sigma}_H + u = K_o \bar{\sigma}_V + u$$

Figure H.1 gives a typical example of stress distribution in situ.

Figure H.2 presents results from laboratory measurements of K_o for a variety of different normally consolidated sands and clays. These data indicate a reasonable agreement with the empirical formula for K_o.

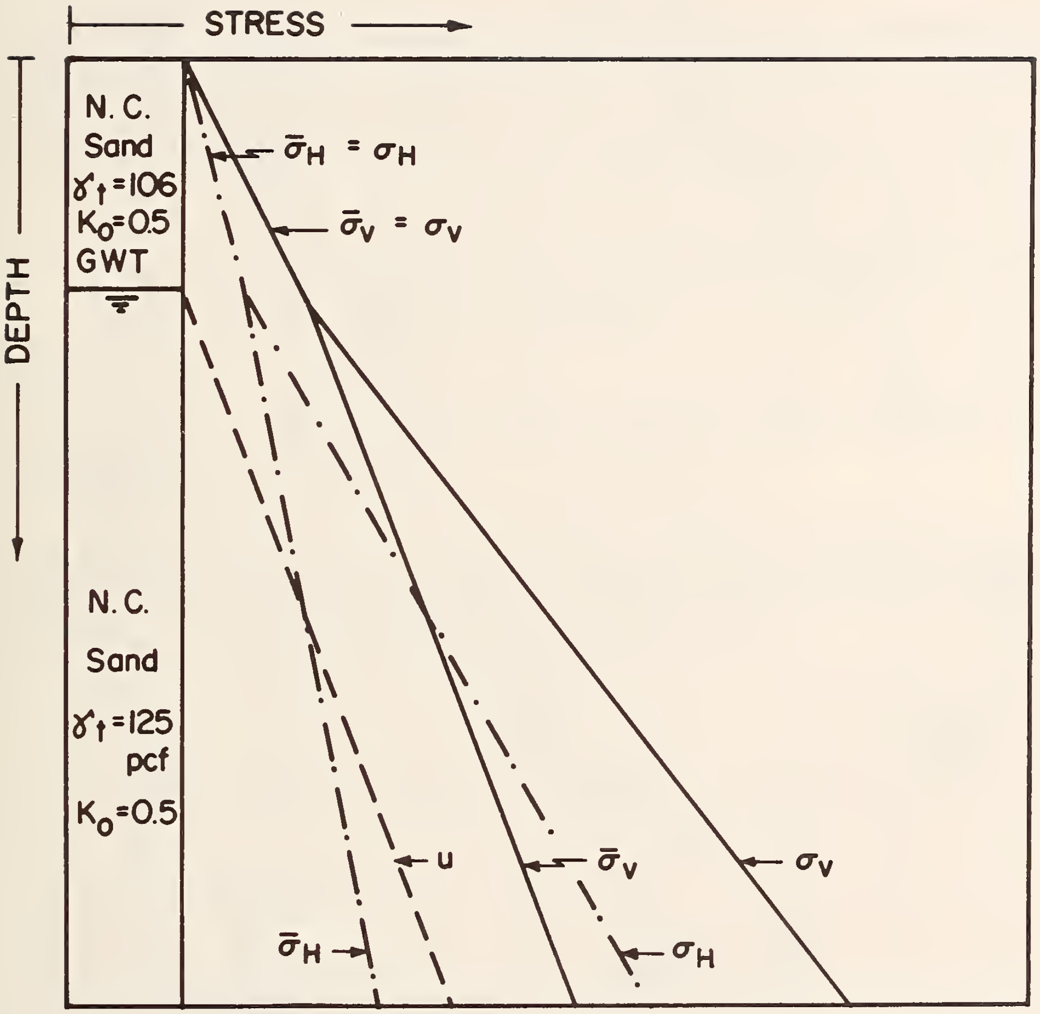


FIGURE H.1 QUALITATIVE STRESS DISTRIBUTION IN SITU

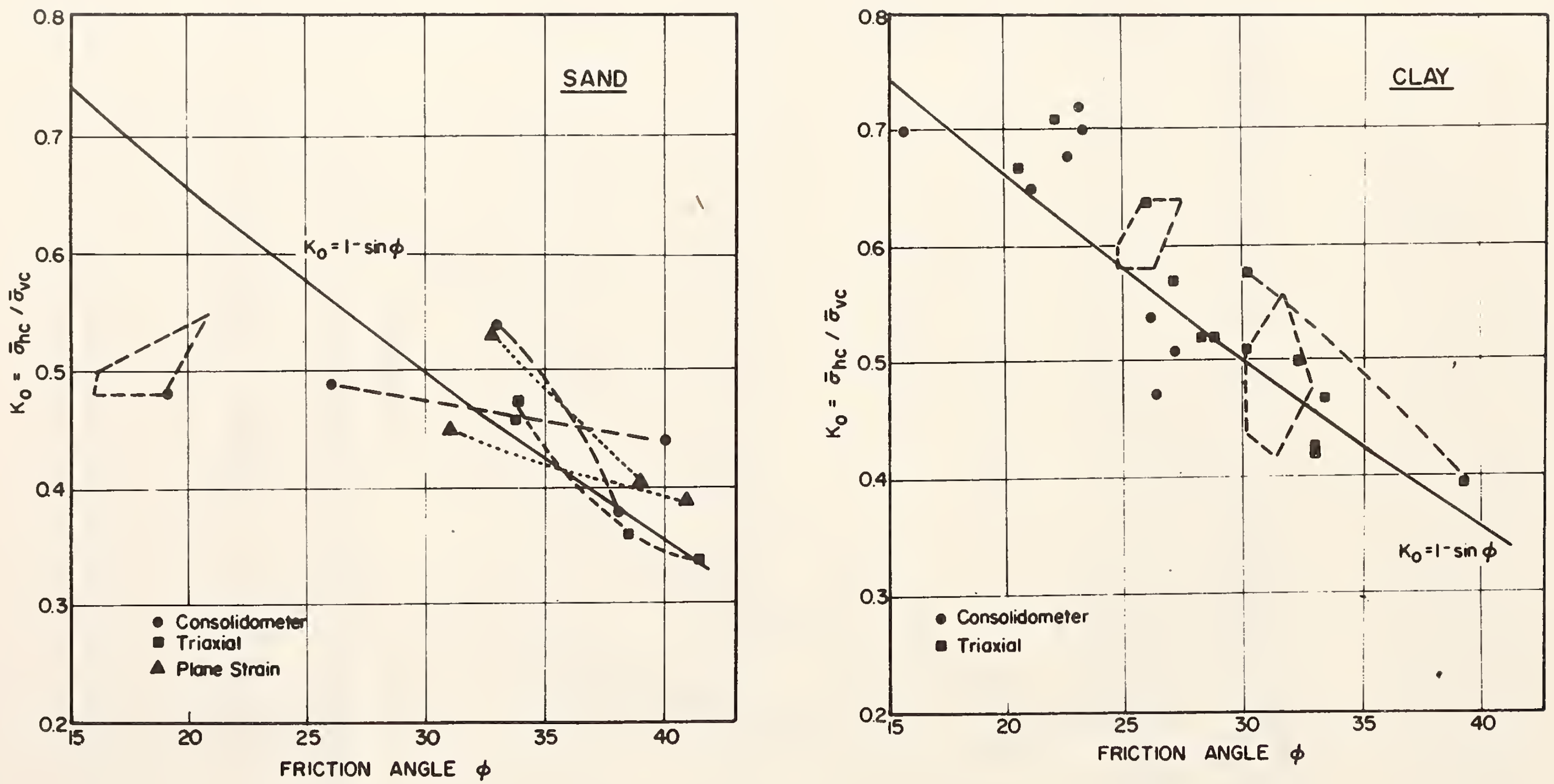


FIGURE H.2 LABORATORY K_o FOR NORMALLY CONSOLIDATED SAND AND CLAY
(After Marr, 1974)

H.3 STRESS DISTRIBUTION AROUND CIRCULAR OPENINGS

When a tunnel or horizontal borehole is excavated in soil, the stress distribution in the vicinity of the opening changes. The magnitude of this change will depend on initial stress conditions ($\bar{\sigma}_h/\bar{\sigma}_v$), soil characteristics, and internal pressure in the opening. No available analytical method today considers all these factors. Available closed form solutions are usually based upon the theory of elasticity.

Elastic and elasto-plastic solutions for stress distribution around underground circular openings follow. The derivation of the equations are readily available in the literature, and will not be given here.

The theoretical solutions are based upon the following assumptions:

(1) The soil is homogeneous and isotropic, (2) The soil behaves in a linear elastic (or perfectly elastic) manner, (3) Young's modulus (E) for compression and extension is equal, (4) The mass around the opening is infinite.

Only the last of these assumptions is approximately true in this case.

ELASTIC STRESS DISTRIBUTION

An infinite plate with a circular opening and different total stress in horizontal and vertical directions ($\sigma_H = K_o\sigma_V$), is applied as a model for the plane strain case of a long, horizontal borehole in soil. The stress around the opening will be:

$$\sigma_r = \frac{\sigma_v}{2}\{(1 + K_o)(1 - \frac{a^2}{r^2}) + (1 - K_o)(1 + \frac{3a^4}{r^4} - \frac{4a^2}{r^2}) \cos 2\theta\}$$

$$\sigma_\theta = \frac{\sigma_v}{2}\{(1 + K_o)(1 + \frac{a^2}{r^2}) - (1 - K_o)(1 + \frac{3a^4}{r^4}) \cos 2\theta\}$$

$$\sigma_a = \mu\,(\sigma_r + \sigma_\theta)$$

where:

σ_r = radial stress

σ_θ = circumferential stress

σ_a = stress parallel to borehole axis

θ = the angle between vertical and the radius

a = opening radius

r = radial coordinate

μ = Poisson's ratio.

If a uniform internal pressure, p_i, is applied in the opening, the solution for $K_o = 1$ will be the following:

$$\sigma_r = \sigma_v \left(1 - \frac{a^2}{r^2}\right) + p_i \cdot \frac{a^2}{r^2}$$

$$\sigma_\theta = \sigma_v \left(1 + \frac{a^2}{r^2}\right) - p_i \cdot \frac{a^2}{r^2}$$

ELASTO-PLASTIC SOLUTIONS

The following section will give the derivation of the resultant stress field around an opening with internal pressure p_i. The original stresses are assumed isostatic, $\sigma_H = \sigma_V$; and $\sigma_{H2} = \sigma_{H3}$. An elasto-plastic material is considered in which the maximum stress difference is

$$\sigma_1 - \sigma_3 = 2c$$

where: σ_1 = major principal stress

σ_3 = minor principal stress

c = cohesion intercept

The equilibrium of a small material element in cylindrical coordinates is:

$$\frac{\sigma_\theta - \sigma_r}{r} - \frac{d\sigma_r}{dr} = 0 \qquad (1)$$

For the plastic zone where σ_θ (tangential) and σ_r (radial) are principal stresses, the yield criterion is:

$$\sigma_\theta - \sigma_r = 2c \qquad (2)$$

The boundary conditions are:

$$\sigma_r = p_i \text{ at } r = a \qquad (3)$$

and $\sigma_r + \sigma_\theta = 2\sigma_v$ at $r = b$ (4)

where: a = radius of borehole

b = plastic zone radius

for equal stress in vertical and horizontal direction ($K_o = 1$).
The combination of (1) and (2) gives

$$\frac{dr}{r} = \frac{d\sigma_r}{2c}$$

and integration gives

$$\ln r = \frac{1}{2c} (\sigma_r + C)$$

With boundary condition (3), the radial and tangential stress are

$$\sigma_r = 2c \ln \frac{r}{a} + p_i$$

$$\sigma_\theta = 2c\ (1 + \ln \frac{r}{a}) + p_i$$

$$\sigma_a = c\ (1 + 2 \ln \frac{r}{a}) + p_i$$

Employing boundary condition (4) yields:

$$\ln \frac{b}{a} = \frac{1}{2} (\frac{\sigma_v - p_i}{c} - 1)$$

or $$b = a \cdot e^{\{\frac{1}{2}(\frac{\sigma_v - p_i}{c} - 1)\}}$$

This formula allows calculations of the plastic zone radius for different internal pressures, vertical stresses and yield strengths. For $\sigma_v - p_i \leq c$, no plastic zone will develop.

For an elasto-plastic material with cohesion, c, and friction, ϕ (strength dependent on normal stress), every point in the yielding zone will be described by the failure envelope.

Daemen and Fairhurst (1973) give as radius of the plastic zone:

$$b = a\ \{(1 - \sin\phi) \frac{\sigma_v + c \cot\phi}{p_i + c \cot\phi}\}^{\frac{1 - \sin\phi}{2 \sin\phi}}$$

Deere et al (1969) give the stress around the opening:

$$\sigma_r = -c \cot\phi + \{(p_i + c \cot\phi) \frac{r}{a}\}^{\frac{2 \sin\phi}{1 - \sin\phi}}$$

$$\sigma_\theta = -c \cot\phi + \{(p_i + c \cot\phi) \frac{1 + \sin\phi}{1 - \sin\phi} \frac{r}{a}\}^{\frac{2 \sin\phi}{1 - \sin\phi}}$$

$$\sigma_a = -c \cot\phi + \{(p_i + c \cot\phi) \frac{1}{1 - \sin\phi} \frac{r}{a}\}^{\frac{2 \sin\phi}{1 - \sin\phi}}$$

For a material with only friction (c = 0), the preceding formulae are valid with the terms containing c equal to zero.

To the authors' knowledge, no closed form solution is available for elasto-plastic material with $K_o \neq 1$. It is possible to obtain an idea of the configuration of a plastic zone for $K_o \neq 1$ by regarding the material as elastic and finding the zones where the shear strength of the material is exceeded. This method is not accurate because the plastic zones redistribute stress.

EMPIRICAL DISTRIBUTIONS AND MEASUREMENTS

The previously treated theoretical solutions all have some unique features: the elasto-plastic solution can take yielding into account;

and the closed form elastic solutions allow different stress magnitudes in horizontal and vertical direction. However, no solution can describe real soil with anisotropic non-linear behavior, and $K_o \neq 1$.

Peck (1969) gives the following formula for stress acting upon a totally flexible liner brought in place with no circumferential strain:

$$\sigma_r = \frac{1}{2}\ \sigma_v(1 + K_o)$$

If circumferential deformations take place, the stress will be changed.

Peck (1969) also refers to the "criterion for stability" (probably excessive squeezing, loss of ground, etc.) developed by Broms and Bennermark for plastic clays. According to this criterion, the ratio

$$\frac{\sigma_v - p_i}{s_u}$$

where: s_u is the undrained shear strength of the clay

should not exceed about 6. This value is based upon case studies from tunnel construction. Because the standup time is both a function of the type of soil and the size of the opening, the criterion would be even more favorable for small diameter boreholes.

Höeg (1965) presents analytical treatment and model test results of pressure distributions on buried horizontal cylinders. For a very flexible and compressible cylinder, in Ottawa sand (K_o = .35 and Poisson's ratio, μ, = .35), his analysis gives a radial pressure equal to 20% of the overburden pressure. Model tests with 4.5 in. diameter steel cylinders padded with 1/8 in. foam rubber under 150 psi overburden yielded a maximum radial stress of 12 psi, or 8 % of the overburden pressure.

H.4 DRILLING FLUID REQUIREMENTS AND BOREHOLE STABILITY

The in situ stress and the type of soil form the basis for the design of the composition of the drilling fluid. In order to assess the potential of mud slurries to stabilize horizontal holes, the following topics, in order, are discussed: (1) fluid pressure distribution in boreholes, (2) filter cake formation, (3) single grain stability, and (4) borehole wall stability.

Drilling fluids suitable for application in horizontal drilling down to 500 ft (150 m) depth will be normal bentonite-water mixtures, with some additives in special cases to adjust viscosity or seal very pervious ground. Bentonite mud is a complex fluid which is usually idealized as a Bingham plastic fluid. Figure F.1a in Appendix F offers a comparison between a Bingham plastic and a Newtonian fluid. The Bingham plastic has a finite shear strength.

FLUID PRESSURE DISTRIBUTION IN BOREHOLES

For the penetration systems considered, drilling fluid (mud) is pumped from the surface through the drill string and downhole motor to the drillbit. From the bit the fluid returns in the borehole annulus (opening between drill string and borehole wall) to atmospheric pressure at the surface.

The static pressure distribution in the annulus depends solely on the specific weight of the mud and the elevation relative to the surface. The unit weight of the mud pumped down should be used in stability design, even though the return flow has a higher density due to suspended cuttings from the drilling process.

FILTER CAKE FORMATION

When drilling a permeable formation with pore openings too small to allow passage of mud solids, the liquid portion of the mud filters into the formation depositing mud solids (filter cake) on the formation surface (see Figure H.3). The permeability of this filter cake will govern the rate of further fluid loss to the formation. With somewhat larger pore openings, mud solids will penetrate the formation and clog the pores. This so-called "deep filtration" has been measured up to several inches (See Figure H.3). The effect will be the same in both cases.

The filter cake acts as a membrane, where the drilling mud pressure on one side and the total formation pressure on the other side maintain equilibrium. Thus the difference, Δp, between mud pressure, p_i, and pore water pressure, u, in the formation will act on the borehole wall as effective stress. Apart from decreasing the rate of fluid loss from the borehole, the filter cake will therefore transfer the following mud pressure to the soil grains:

$$\Delta p = p_i - u = \gamma_f \cdot z - \gamma_w \cdot z$$

For very porous soil (e.g. gravel) the slurry might penetrate several feet before being resisted by the shear stress between soil and slurry (rheological blocking). The soil immediately around the borehole will then only experience a small portion of the mud pressure as effective stress and stability will be endangered. This effect is demonstrated in Figure H.3. Transferral of mud pressure to effective stress is assumed linear in the zone of rheological blocking. See Müller-Kirchenbauer, 1972, for a thorough treatment of this subject. Thus the soil in the borehole wall will be without support from the drilling mud. High bentonite concentration or additives (i.e. cellophane flakes, sawdust) in the drilling fluid will help to build the needed filter cake in very pervious soil.

Apart from the soil's pore size and the permeability, a second factor is necessary for filter cake formation: the water head in the drilling mud must be higher than the water head in the soil, so flow

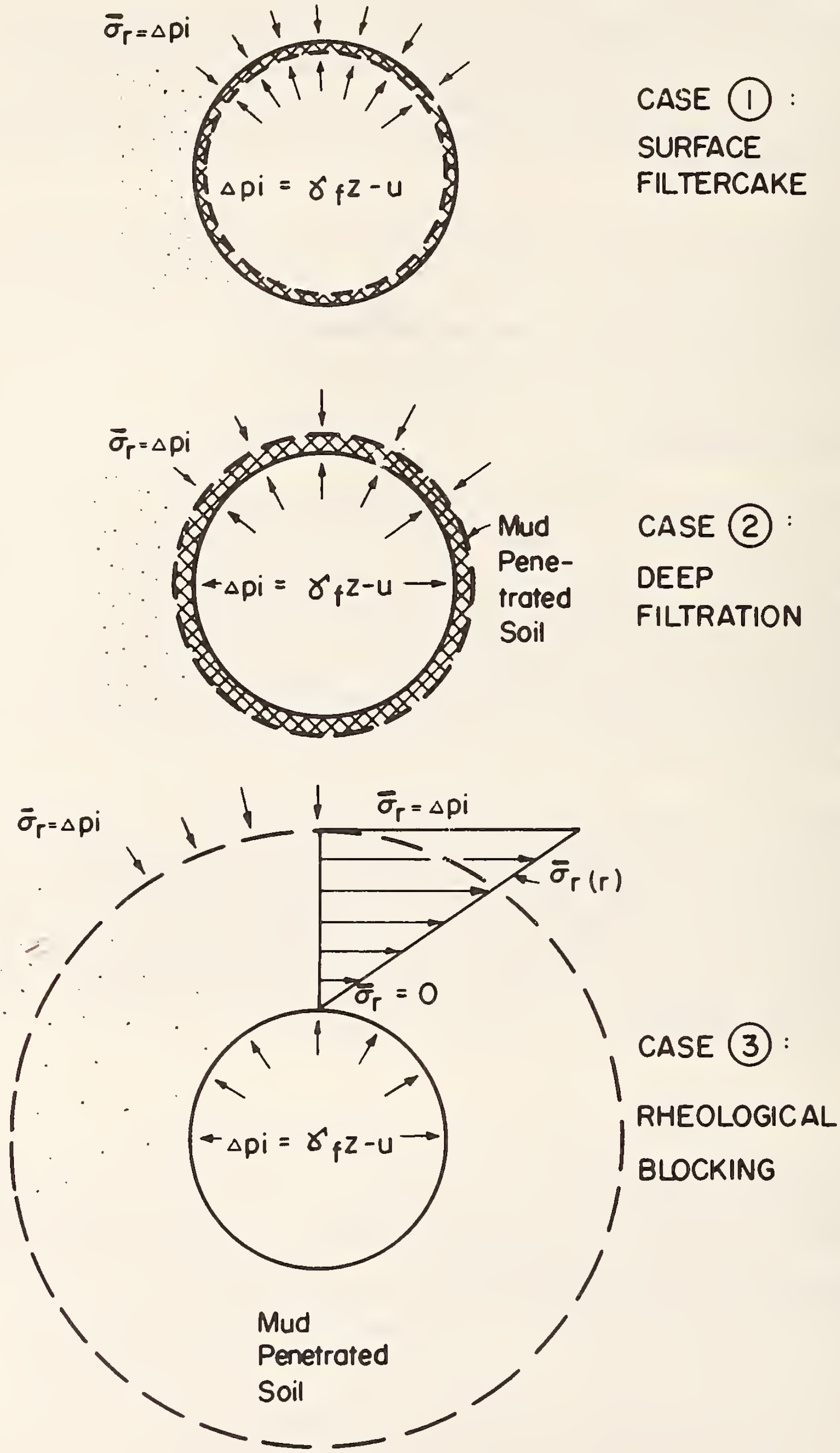


FIGURE H.3 EQUILIBRIUM BETWEEN FORMATION AND DRILLING MUD PRESSURE

of drilling mud water into the soil is possible. Therefore, cohesionless soil layers with artesian water pressure cannot be drilled until the high stratum pressure is released.

In cohesive soil no filter cake is formed because the permeability is too low, even for water penetration.

Weiss (1972) has given the following formula to estimate the distance drilling mud will penetrate permeable formations:

$$1 = c_1 \cdot c_2 \cdot \sqrt{\frac{k}{n}} \cdot \frac{\Delta P}{2\tau_F}$$

where: $c_1 = \left(\frac{8\eta}{\gamma w} = 1.031 \cdot 10^{-2} \text{ cm}^{1/2} \text{ sec}^{1/2} \right)$ is a viscosity constant formed by the viscosity of water, η, and the water unit weight, γw.

c_2 = a constant dependent on the pore system in the soil. Laboratory tests with gravel have given c_2 ranging from 3.43 to 8.69, with 5 as the mean value (Weiss, 1967).

k = coefficient of permeability

n = porosity

Figure H.4 gives apparent mud shear strength for different bentonite concentrations based upon Weiss ball viscometer. This curve is only valid for 20° C and for one bentonite type (Tixoton). Different bentonite brands will give different shear strength lines due to presence of contaminants and some percentage of other clay minerals. Based on this mud strength, the penetration distance is computed for different bentonite concentrations, and permeability/porosity ratios.

Figure H.5 gives the mud penetration distance for 14.2 psi (9.8 N/cm^2) pressure difference between the drilling mud and the pore water. This pressure difference corresponds to a depth of 79.7 feet (23.9 m) if the groundwater table is at 10 ft (3 m) depth for a 5.5% (by weight) bentonite mud. There is a linear relationship between pressure difference and penetration distance, so the graph can be employed for any pressure by a simple multiplication.

The following is an example of how the graph is constructed and can be used:

A fine sand having the permeability coefficient $k = 5 \cdot 10^{-3}$ cm/sec (from laboratory permeability tests, pumping tests or empirical correlations) and a porosity $n = 0.5$ (from density measurements) has the permeability/porosity ratio $\frac{k}{n} = 10^{-1} \text{ cm}^{1/2} \text{ sec}^{-1/2}$. The drilling mud as a bentonite concentration of 20 lb/bbl (57 kg/m^3 or 5.5% by weight). From Figure H.4, 20 pd/bbl (57 kg/m^3) bentonite results in

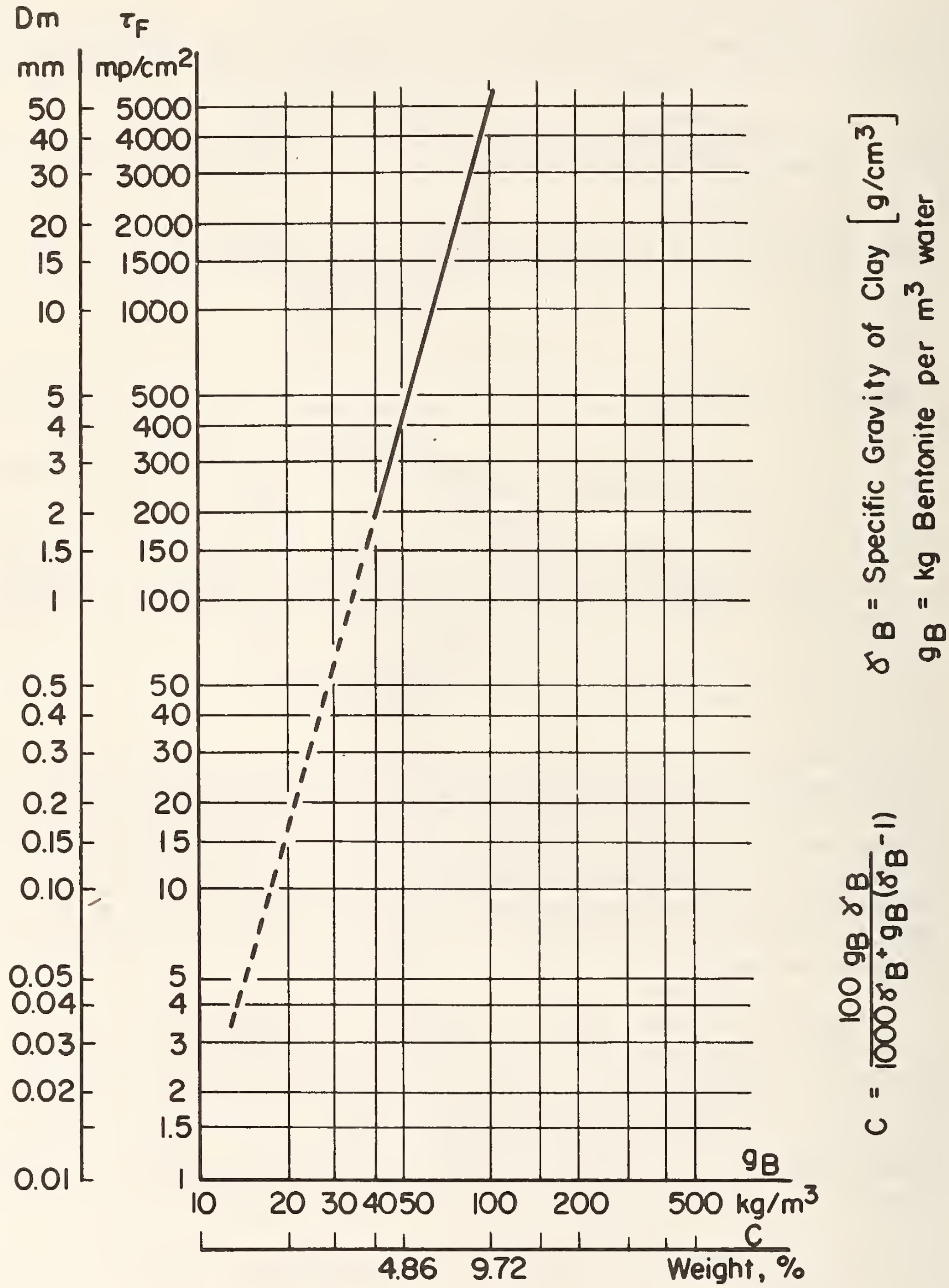


FIGURE H.4 APPARENT MUD SHEAR STRENGTH AT DIFFERENT BENTONITE CONCENTRATIONS (After Weiss, 1972)

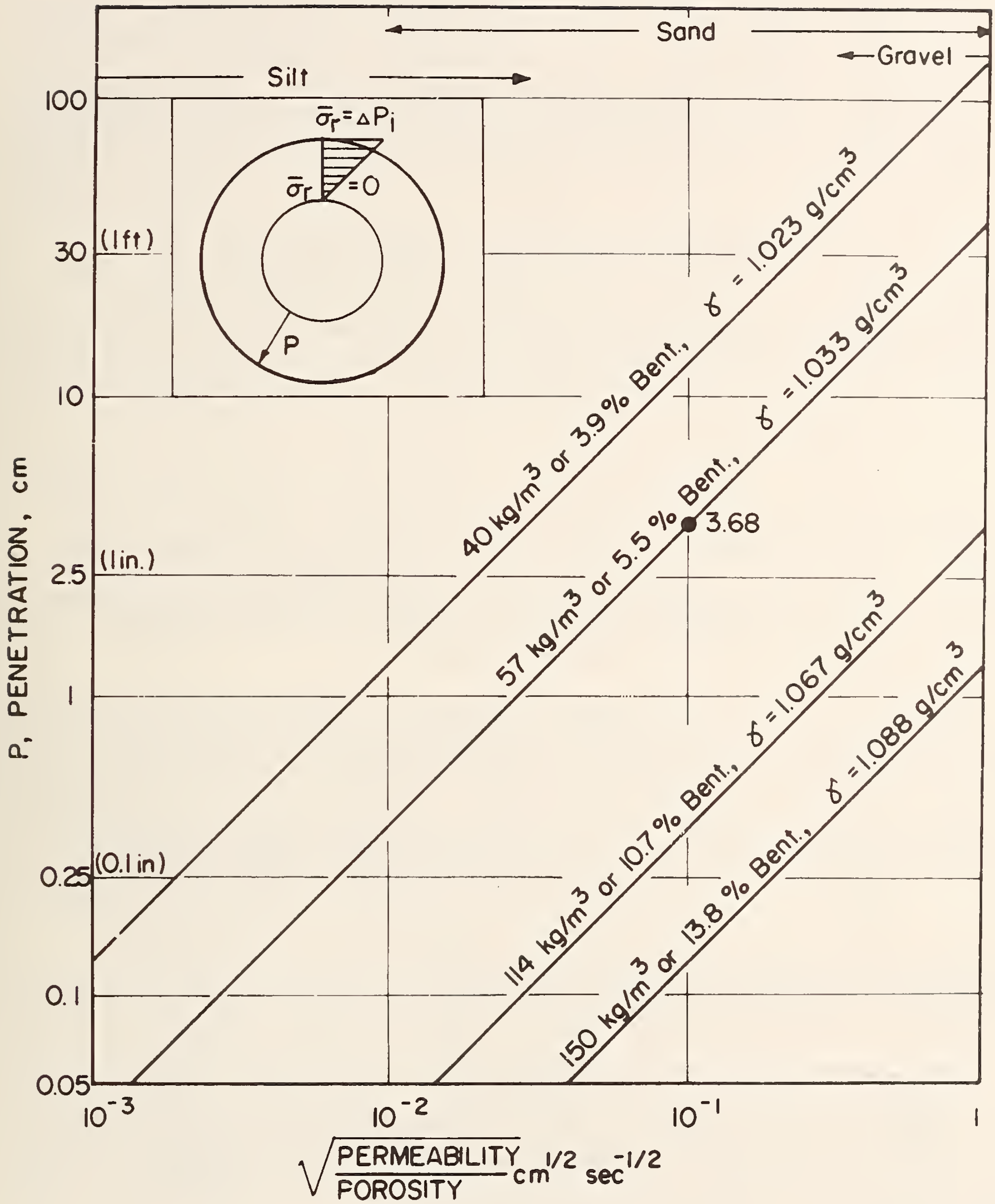


FIGURE H.5 DRILLING MUD PENETRATION BY 14.4 PSI ($1 kg/cm^2$) PRESSURE DIFFERENCE BETWEEN MUD AND POREWATER

a mud shear strength of 700 mp/cm^2 (1.43 psf or 68.6 N/m^2).

$$1 = c_1 \cdot c_2 \cdot \sqrt{\frac{k}{n}} \cdot \frac{\Delta P}{2\tau_F}$$

$$= 1.031 \cdot 10^{-2}\ cm^{1/2}\ sec^{1/2} \cdot 5 \cdot 10^{-1}\ cm^{1/2}\ sec^{-1/2} \cdot \frac{1000\ g/cm^2}{2 \cdot 0.7\ g/cm^2}$$

$$= 3.68\ cm = 1.45\ in.$$

At the top of Figure H.5 are indicated typical permeability/porosity ratios for different soil types. The penetration depth should not exceed 1/2 to 1 in. (1 to 2 cm), which is the borderline between deep filtration and rheological blocking. As shown in Figure H.3, rheological blocking leaves the immediate borehole wall without support from the drilling mud, and thus endangers the borehole stability.

SINGLE GRAIN STABILITY

There are two stability requirements that must be fulfilled to keep the borehole from collapsing: (1) The single grains in the borehole wall must be stable and not fall out (only required for cohesionless soil), and (2) The mud pressure exerted on the borehole wall must be sufficient to balance the radial soil stress around the borehole and to decrease creep to an acceptable level.

Figure H.4 also gives the grain diameters D_m that can be supported at different mud shear strengths as measured with a ball viscometer. These grain sizes are computed with a formula given in Weiss (1972) and a factor of safety (F.S.) equal to three. As can be seen from Figure H.4, 20 pd/bbl (57 kg/m^3) bentonite concentration (5.5%) already provides a mud with strength to carry a .27 in. (7 mm) diameter grain suspended (F.S. = 3). From model tests, Weiss (1967) concluded the maximum grain size in a given soil did not have to be supported to ensure stability. Only 25% of the finest material need be supported to protect against failure. However, some coarse material would fall out of the wall. Weiss's grain-size study may not adequately model surface tension and is therefore controversial. However, it represents one approach.

The upper grain-size limit for sand is .1 in. (2 mm) diameter, so Weiss's data ensures single-grain stability in any sand. However, as shown in Figure H.5, a good filter cake will not likely be developed in coarse sand with this mud concentration, and will require a high bentonite concentration. In general, it seems that if a filter cake is formed, single-grain stability will be ensured.

BOREHOLE WALL STABILITY

The radius of the plastic zone in a cohesive soil (see Figure H.2) was found to be

$$b = a \cdot e^{\{\frac{1}{2}(\frac{\sigma_v - p_i}{c} - 1)\}}$$

If the values of σ_v, p_i, and c are normalized with regard to the depth z, typical values of the plastic zone radius can be obtained. The normalized vertical stress σ_v/z will typically range from 95 psf/ft (15 $N/cm^2/cm$) in dense, sat. soil. The drilling mud pressure with no circulation p_i/z will vary from 65 to 80 psf/ft (10 to 13 $N/cm^2/cm$) for water based muds. No circulation pressure is the most conservative case provided there is no loss of fluids. For short term stability, the normalized yield strength c/z will be equal to s_u/z, where

$$\frac{s_u}{z} = \frac{s_u}{\bar{\sigma}_v} \cdot \frac{\bar{\sigma}_v}{z}$$

As $s_u/\bar{\sigma}_v$ will vary from .2 to .5 and $\bar{\sigma}_v/z$ from 50 to 75 psf/ft below the water table, s_u/z will have values ranging from 10 to 37 psf/ft (1.5 to 6.2 $N/cm^2/cm$).

Employing the preceding values, $\frac{\sigma_v - p_i}{s_u}$ can range from 1 to 7.5 in extreme cases. The typical range can be estimated

$$\frac{\sigma_v}{z} = 120 \text{ psf/ft}, \quad \frac{p_i}{z} = 65 \text{ psf/ft}, \quad \frac{\bar{\sigma}_v}{z} = 55 \text{ psf/ft and } \frac{s_u}{\bar{\sigma}_v} = 0.3 \pm .1$$

with $\frac{\sigma_v - p_i}{s_u}$ = 2.5 to 5 (for normally consolidated soils)

which gives the radius of the yielding zone b = 2 to 7 a.

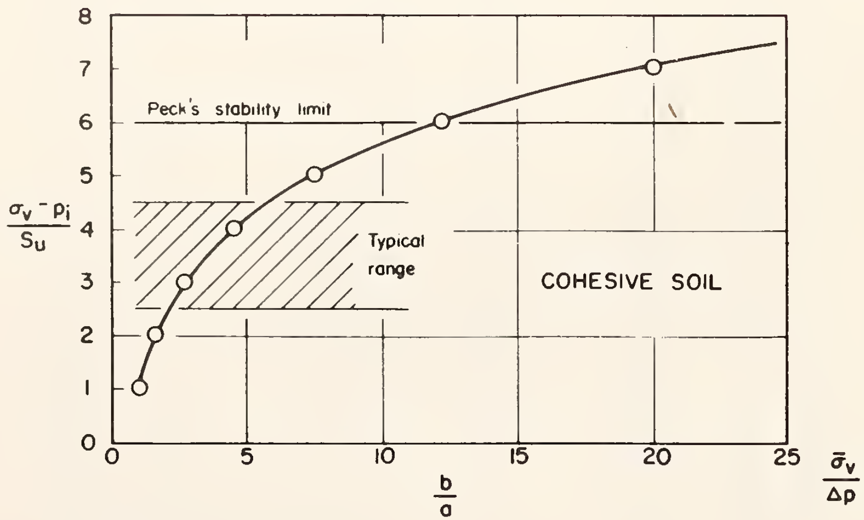
In Figure H.6 the plastic zone radius is plotted as a function of $\frac{\sigma_v - p_i}{s_u}$.

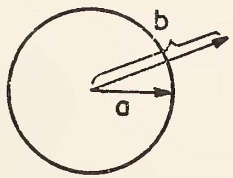
As referenced in Section H.3, Peck (1969) gives as criterion for stability of tunnels in cohesive soil:

$$\frac{\sigma_v - p_i}{s_u} < 6$$

Plotted in Figure H.6 this criterion indicates that stability is ensured for yielding zone radii up to 12 a . Thus, the typical range of normally consolidated cohesive soils will be stable, as will all overconsolidated soils, which have higher normalized undrained strengths. Only very soft soils with a $s_u/\bar{\sigma}_v$ less than 0.2 may have endangered stability by normal mud densities. However, with p_i/z = 75 psf/ft (11.5 $N/cm^2/cm$), s_u/z can have values down to 0.12 without exceeding Peck's criterion.

From this theoretical and semi-empirical treatment, it seems possible to ensure stability of horizontal boreholes in most cohesive soils. Where the soil has very low undrained shear strength, heavier drilling mud must be employed. In unconsolidated sediments, stability is not likely. These results need to be verified by field tests and measurement of creep and stand-up behavior with time.





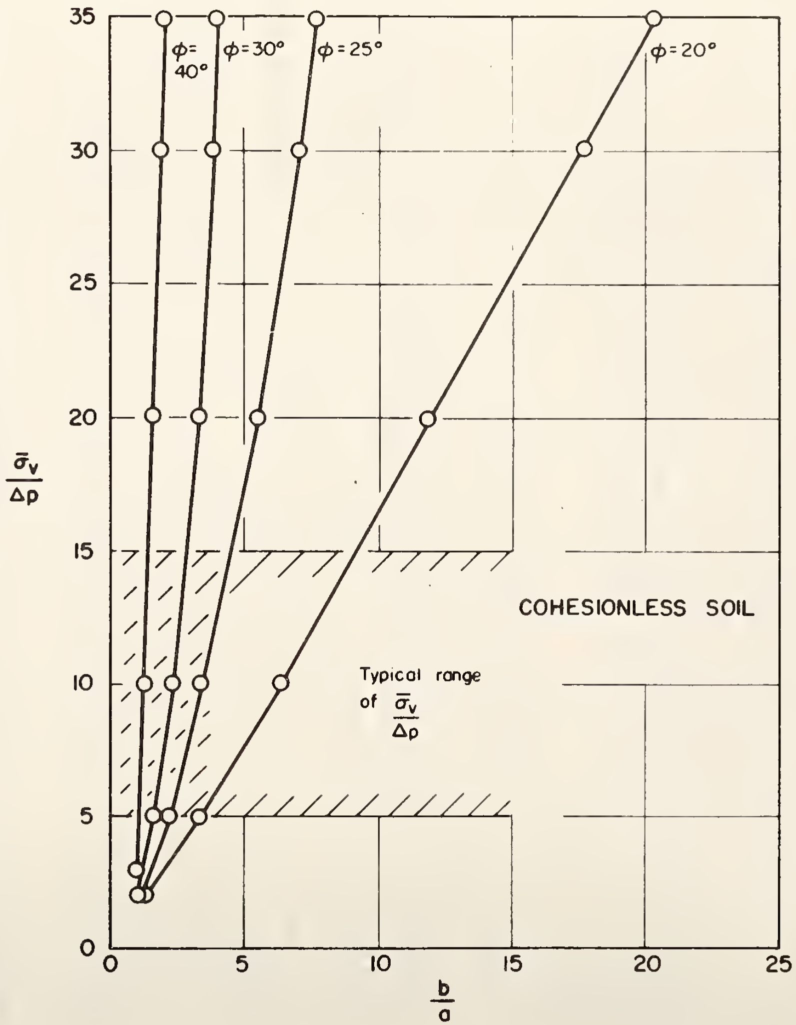


FIGURE H.6
PLASTIC ZONE RADII
COHESIVE AND COHESIONLESS
SOILS

The radius of the plastic zone in cohesionless medium is:

$$b = a \left\{(1 - \sin \phi) \frac{\sigma_v}{p_i}\right\}^{\frac{1 - \sin \phi}{2 \sin \phi}}$$

A closer examination of this formula reveals that p_i is the drilling mud pressure transferring support to the borehole wall. If the borehole is below the groundwater table, the correct expression for this support pressure is $\Delta p = p_i - u$. Similarly, σ_v should be the effective soil stress, which below the water table is $\bar{\sigma}_v = \sigma_v - u$. The complete formula from H.3 will therefore be:

$$b = a \left\{(1 - \sin \phi) \frac{\bar{\sigma}_v}{\Delta p}\right\}^{\frac{1 - \sin \phi}{2 \sin \phi}}$$

In a dry soil the most unfavorable values for stability will be: soil friction angle $\phi = 20^o$ and $\bar{\sigma}_v/\Delta p = 2.0$ ($\bar{\sigma}_v/z = 125$ psf/ft and $\Delta p/z = 62.5$ psf/ft). These values will give $b = 1.3\,a$. This small size of the yielded zone means that in dry, granular soil the plastic zone will be very limited or not develop at all.

Results from Höeg (1965) were given in Section H.2 With Höeg's analysis, the radial stress in a horizontal opening in sand is 20% of the vertical stress. By using his model tests the radial stress is only 8% of the overburden.

Below the groundwater table, $\bar{\sigma}_v/\Delta p$ can range considerably depending mainly on the drilling mud density and elevation difference between mud level and groundwater. Figure H.6 gives the yield radius as a function of $\bar{\sigma}_v/\Delta p$ would be 5 to 15, with radii of yielding zones varying from 1 to 3 a for $\phi = 30 - 35^o$. An extremely high value of $\bar{\sigma}_v/\Delta p$ would be 30: for groundwater table equal to slurry level, $\bar{\sigma}_v/z = 62.5$ psf/ft (10 N/cm) and $\Delta p/z = 2$ psf/ft (.27 N/cm) (5.5% bentonite concentration).

The small plastic zone and radial stress--which are indicative of relatively stable conditions--are dependent upon the existence of Δp. The moment Δp is lost a much larger failed zone will develop.

In conclusion: Although in most soils a yielding zone will develop around horizontal boreholes, the extent of this yielding zone is predicted by the theory to be finite. This indicates ultimate stability, and that the soil is able to stand-up around horizontal boreholes with only the support from the drilling mud. However, if hydraulic fracture or loss of circulation occurs, the mud pressure difference will decrease and instability may result.

The yield radii were calculated assuming that Δp resulted only from the static mud pressure. During drilling the normalized mud pressure at the bit will be greater than 2 psf/ft (approximately 75 - 100 psf/ft) because of the excess pressure needed to recirculate the fluids. However, there will always be non-drilling periods and therefore the static case will occur sometime during any operation.

In permeable cohesionless soil, the drilling mud must be capable of forming a filter cake with no more than 1 - 2 cm penetration depth. Larger penetration will mean effective stress transformation from the mud to the soil over a larger distance, which results in limited support of the immediate borehole wall (See Figure H.3). Single grain stability appears to be ensured as long as a filter cake can be formed.

It should again be pointed out that all these results are based on theory and model studies. Only field testing in a rigorous manner can give definite proof of their validity.

H.5 CHANGE IN STRESS STATE AND TIME EFFECTS

For the purpose of employing borehole logging tools or exploration units after the drilling of the hole is completed, stability must be ensured over a larger time span.

Over consolidated soils lose strength with time, but will permally retain more than enough strength for stability. Fissured clay may be susceptible for stability problems with time.

Normally consolidated soils gain strength with time and consolidation. The borehole excavation leads to higher stress in the soil surrounding the borehole ($K_o = 1$) since this soil will have to carry some of the stress previously placed on the excavated material. In Figure H.7 typical stress paths are shown for borehole wall elements with the $K_o = 1$ (total stress) elasto-plastic stress solution given in Section H.3. The soil starts from an isostatic condition with $\sigma_V = \sigma_H$. The radial stress then drops off to p_i, which is 60 - 80% of σ_V. The circumferential stress then increases to $p_i + 2\,s_u$ (yielding) or $2\sigma_V - p_i$ (elastic). The effective stress path (ESP) will thereby go from (a) to (b), the total stress path minus initial pore pressures (TSP) from (a) to (c). With consolidation, the effective stress path goes from (b) to (c), thereby moving away from the failure line. The soil thus gains strength with time. The stress paths will differ for $K_o \neq 1$.

Cohesionless soils do not change strength with time. The mud level in the hole must always be kept well above the groundwater.

The contact between water based drilling mud and clay borehole walls might cause swelling of the clay, and slow closure of the hole. The swelling is believed by Titan Contractors to occur in the "gumbo" clays. Oil base muds are employed there to prevent swelling. Oil would, however, destroy the rubber stator in Dyna-Drill, so in case oil mud is needed, the water mud can be replaced after completed excavation.

In soils where creep and strength loss with time is experienced, long time stability might also be endangered. The closure or collapse of a borehole would give some indication of the strength and stand-up behavior of the soil, and provide useful information for tunneling construction.

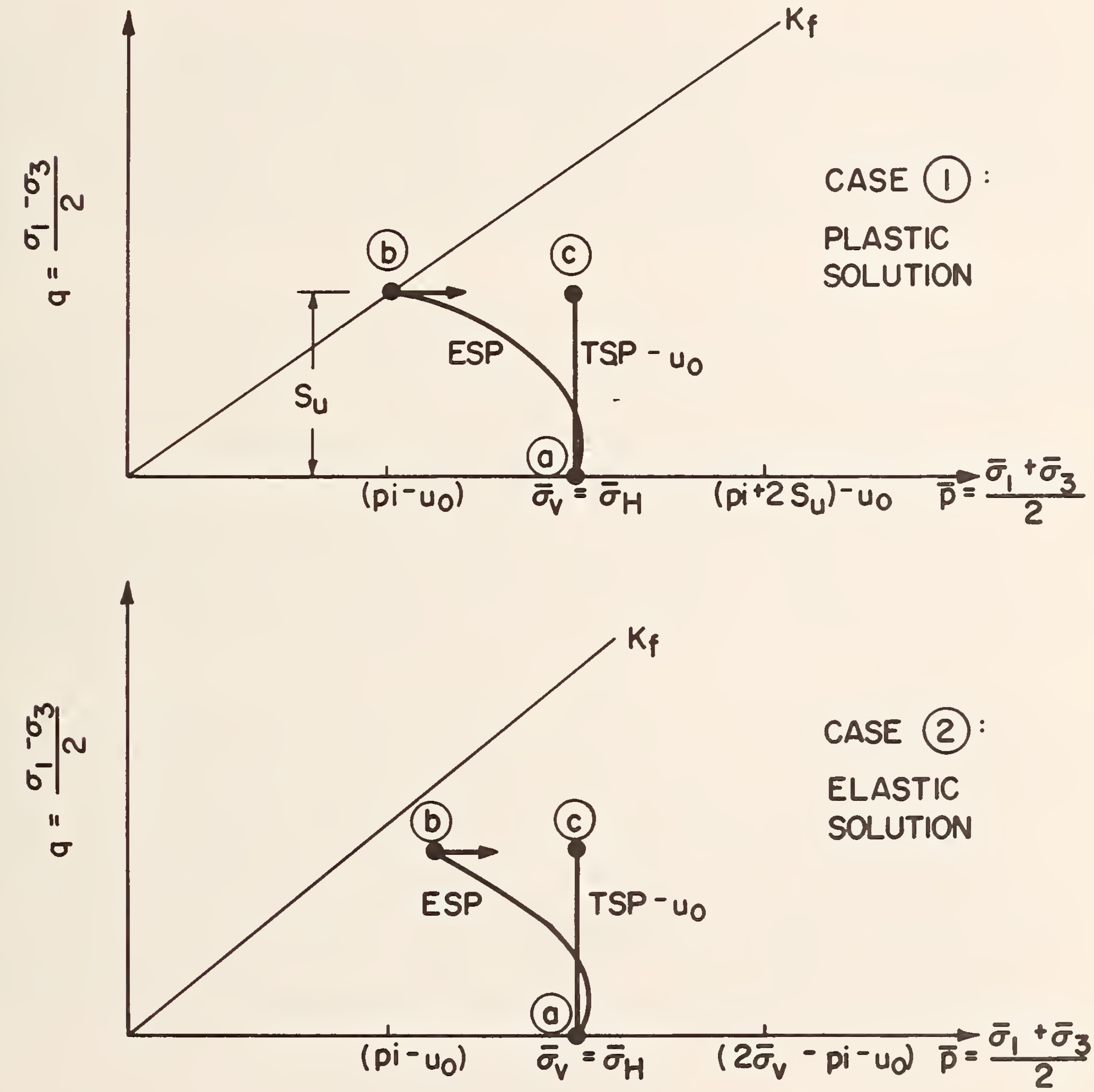


FIGURE H.7 STRESS PATH FOR ELASTIC AND PLASTIC ELEMENT IN BOREHOLE WALL (N.C. CLAY σ_H/σ_V (Initial) = 1)

APPENDIX I

SOIL DISTURBANCE AROUND HORIZONTAL BOREHOLES

I.1 INTRODUCTION

The excavation equipment suitable for advancing horizontal boreholes in soft ground was described in Appendix D. The mechanical action of this equipment includes the following: rotation of the drill bit, circulation of drilling mud, load from anchor shoes or deflection shoes and sliding of drill string or umbilical cable through the borehole. As discussed in Appendix H, the mere presence of a borehole will change the stress field in the borehole vicinity from the original in situ state.

Both the mechanical action and the stress redistribution will disturb the soil surrounding the borehole, and thereby change the engineering properties of this soil. Subsequent measurements of soil parameters in the disturbed zone will then not reveal the true in situ properties. It is therefore important to determine the presence and extent of any disturbance, and the possible effect the disturbance will have on measured properties. With a knowledge of the borehole disturbance, the reliability of the measurements can be verified and misleading or wrong information disregarded. Exploration which does not yield the true value of some in situ property or which does not permit back calculation of the true value is a poor investment of money and effort.

A comparison of the disturbance around horizontal exploration holes and normal vertical boreholes might aid in deciding which measurement methods will yield valuable information in horizontal holes. A good deal of experience regarding in situ testing in vertical holes exists which permits translation of the measured properties to the true in situ values as backfigured from the behavior of subsequent constructions. Thus if the nature and extent of the disturbance is the same around horizontal and vertical holes, the existing experience from vertical holes can be employed to correct parameters measured in horizontal boreholes. The disturbance will only represent some inconvenience, and not reduce the value of measuring disturbed parameters.

I.2 EXCAVATION PROCESS

The specific processes in the borehole excavation that might influence the soil around the hole are:

1) Rotation of the drill bit and jetting of the drilling mud from bit nozzles

2) Bearing of the thrust applicator anchor pads and the deflection shoe against the borehole wall

3) Sliding and bearing of drill string or umbilical cable along and against the borehole wall

4) Circulation of the drilling mud (with cuttings) along the borehole wall.

The disturbance effect of these four excavation-related actions will be discussed in the subsequent sections.

DRILLBIT DISTURBANCE

The design of all four different excavation systems foresees the use of tricone rotary bits. The rotation speed of the bits will be 150-300 rpm (revolutions per minute) for the electric motor, 300 rpm for the 5 in. diameter Nichols hydraulic motor, 1000 rpm for the 2 3/8 in. diameter Dyna-Drill and 410 rpm for the 6 1/2 in. diameter Dyna-Drill. Milchem (1973) reports that rotary speeds above 100 rpm tend to compact cuttings into the borehole wall. With the high rotary speeds of the Dyna-Drills, it is then very likely that such centrifugal compaction will occur. The only way to assess its magnitude would be to compare the tailings during drilling with the theoretical excavated volume. This is only possible if no drilling mud is lost, and the cuttings can be separated from the mud.

The drilling mud flow rate past the bit is 30 gpm (0.11 m^3/min) for the electric motor, 32 gpm (0.12 m^3/min) with the 2 3/8 in. diameter Dyna-Drill, 225 gpm (0.85 m^3/min) for the 5 in. diameter Dyna-Drill, and 325 gpm (1.24 m^3/min) for the 6 1/2 in. diameter Dyna-Drill. The mud jetting through the bit nozzles might erode a cavity in front of the drillbit. This is most likely to occur with the two large diameter Dyna-Drills, where the ratio of mud flow to borehole area is highest. Only field tests can give conclusive information concerning the possible extent of face erosion.

Installation of so-called dump valves shown in Figure I.1 might enable control of this erosion during periods of slow advance. The dump valve allows a part of the drilling mud to flow into the borehole annulus between the motor and the drillbit. As the pressure loss across the bit is fairly high, the dump valve must be shaped to dissipate energy, so no turbulence and borehole erosion occurs.

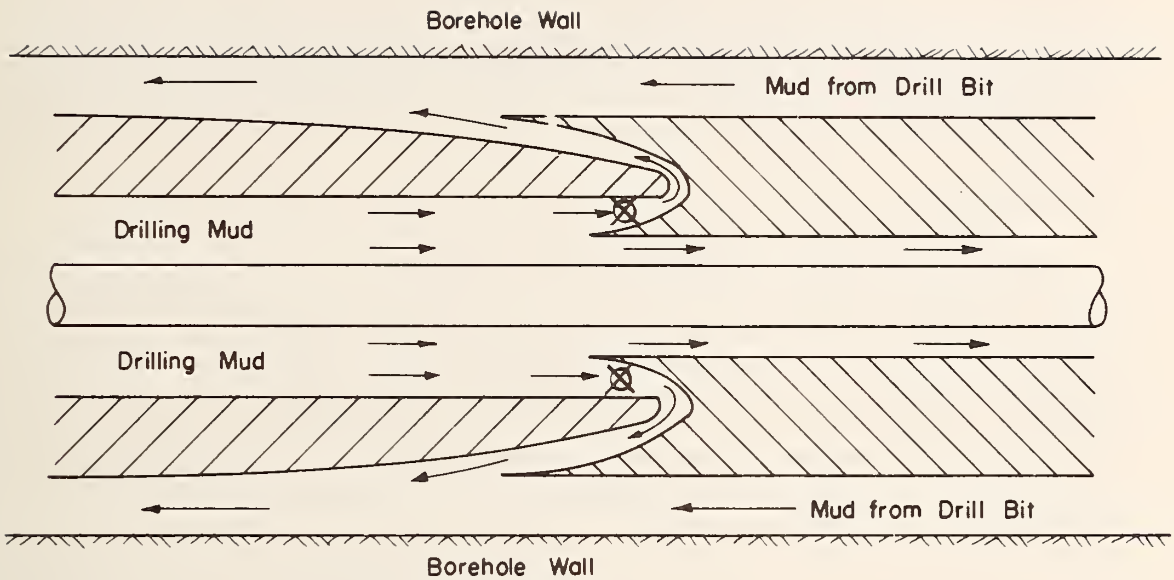


FIGURE I.1 SCHEMATIC CROSS - SECTION OF DUMP VALVE ⊗

ANCHOR PADS

Thruster excavation employs a thrust applicator for propulsion. The thrust applicator has extendable pads to anchor against the borehole wall for reaction of the normal force on the drillbit. The present design includes 1 in. (2.5 cm) wide and 6 in. (15.2 cm) long pads around the circumference. Pad sizes will have to be increased for soft ground excavation as indicated in Appendix G. When anchored against the soil, the pads will compact and/or disturb the soil somewhat. The size of this disturbed zone is assumed to be equal to the failure zone for limiting equilibrium (Prandtl solution). In cohesive soil (ϕ =0)

the depth of the failure zone will be 0.7 times the pad width (Janbu, 1973). In cohesionless soil the depth of the failure zone is dependent on the friction angle and will range from 1 to 2 times the pad width. The depth of this disturbance will then not exceed one radius from the borehole wall with the small anchor pads presently employed. Larger pads will increase this depth of disturbance.

The deflection shoe is used to change direction and will produce disturbance at only one side of the hole circumference. The shoe is circular with the same radius as the downhole motor, which is approximately half the borehole radius. The size of the disturbed zone produced by the deflection shoe can be evaluated with limiting equilibrium as done for the anchor pads. The disturbance depth will not exceed one borehole radius.

DRILL STRING

The drill string in mandrel excavation is non-rotating, and has as its main function the transfer of normal force to the drillbit and drilling mud to the downhole motor. The high normal forces necessary to advance long boreholes might cause buckling of the drill string. Buckling was observed between the drill string supports on the Titan Contractors' rig at the Cerritos Channel job in Long Beach. The moment of inertia, the support, the normal force and the curvature at any one point of the drill string will govern buckling. The magnitude of the contact pressure between the buckled drill string and the borehole wall will depend on the same parameters. Provided the soil is strong enough to withstand the drill string pressure, the depth of the disturbed zone will be less than one borehole radius, based on limiting equilibrium analysis.

In curved boreholes there will be a tendency to "key," i.e., the drill string erodes a slot in the inside wall of the curve. In horizontal drilling with downhole motors, "keying" should be much less pronounced than in vertical drilling with rotating drill strings. The thruster umbilical cable is flexible, and will therefore cause even less disturbance to the borehole wall.

In soft, cohesive soil "crabbing" might occur during course changes; i.e., the soil cannot provide enough support for true turning and the motor advances angularly in the hole. The soil wall will therefore be in the state of failure, and the failure surface will have a depth of 0.7 times the diameter of the excavation equipment (limit equilibrium failure surface). The borehole will therefore have an elliptical rather than circular shape due to the "crabbing."

DRILLING MUD

Drilling mud will penetrate pervious soil as described in Section H.4 and Figure H.5. This penetration must be kept small to ensure stability of the borehole. Thus whenever pervious soil is

expected, the drilling mud must be changed accordingly in advance, i.e., more bentonite or additives must be mixed into the mud. If excessive mud penetration should occur, the increased clay content will change the soil properties to some degree. Fernandez-Renau (1972) report conflicting opinions among various authors as to whether mud penetration increases or decreases the soil friction angle. To ensure stability penetration depth should be kept below 1-2 cm. However, if pervious zones are unexpectedly encountered, the penetration might exceed this value considerably, possibly leading to total collapse of the borehole.

Drilling mud circulating in the borehole annulus might cause erosion of the borehole wall. Appendix F discussed erosion of the filter cake, and concluded that further testing was necessary to obtain conclusive information. However, as long as the mud flow was laminar, theoretical considerations indicated no danger of erosion.

The mud pressure during drilling at the bit was found in Appendix F to be higher than the static mud head. This is caused by the frictional resistance to flow in the borehole annulus. The higher mud pressure is more likely to cause hydraulic fracturing of the ground which permits mud to flow deep into the soil formation. When Titan Contractors drilled below the Cerritos Channel in Long Beach, drilling mud from the 100 ft (30.5 m) deep hole percolated all the way back to the surface. Such extensive fracturing will lead to severe disturbance of the soil, and change both strength and permeability characteristics near the fractures.

DISTURBANCE FROM EXCAVATION--SUMMARY

To summarize the findings of the previous discussion: The rotation speed of the drillbit might compact cuttings into the borehole wall. The extent of this compaction effect is not known. Drilling mud erosion in front of the drill bit will occur, but can most probably be controlled by dump valves. The anchor pads and deflection shoe will not cause disturbance beyond one radius depth. Crabbing disturbs soil one diameter beyond the hole which may be eliptical. "Keying" will only occur in curves if a substantial length of drill string has passed by. Drilling mud penetration and hydraulic fracturing of the borehole wall can be partially anticipated and often prevented by correct mud composition. However, when hydraulic fracturing does occur, it can be extensive.

The manner of sampling in exploratory vertical boreholes precludes most of the above problems. The process of excavating is normally terminated two diameters above the sampled zone. However, the stresses in the soil around vertical boreholes will be redistributed, although to a lesser extent than around horizontal boreholes. This redistribution is important for borehole dilatometer and shear tests in vertical holes.

I.3 STRESS REDISTRIBUTION AROUND BOREHOLES

When a borehole in soil is excavated, the in situ stress field adjacent to the hole will change (See Appendix H). This section will treat the disturbance in the soil resulting from the stress change, and the often accompanying deformations around and in front of the borehole. Stress changes and disturbance will be compared between horizontal and vertical holes. If the disturbance is similar, empirical values of its influence on soil parameters obtained from vertical holes can be utilized for horizontal holes.

BOREHOLE CIRCUMFERENCE

The theoretical solutions for stress distribution around horizontal circular openings ($\sigma_H / \sigma_v = 1$) coupled with yielding criteria of the soil gave the radii of plastic zones shown in Figure H.6. In typical, normally consolidated, cohesive soils the radius of the yielded zone will range from 2 to 7 times the opening radius, and in cohesionless soils below the groundwater table, from 1 to 3 times the opening radius (See Section H.4). These values are all based upon equal stress in the soil in horizontal and vertical direction (K_o=1). If the horizontal stress is lower than the vertical (which always is the case in normally consolidated soils), the plastic zone will probably be eliptical as shown in Figure I.2 (Einstein, 1975). The size increase of the plastic zone cannot be readily quantified.

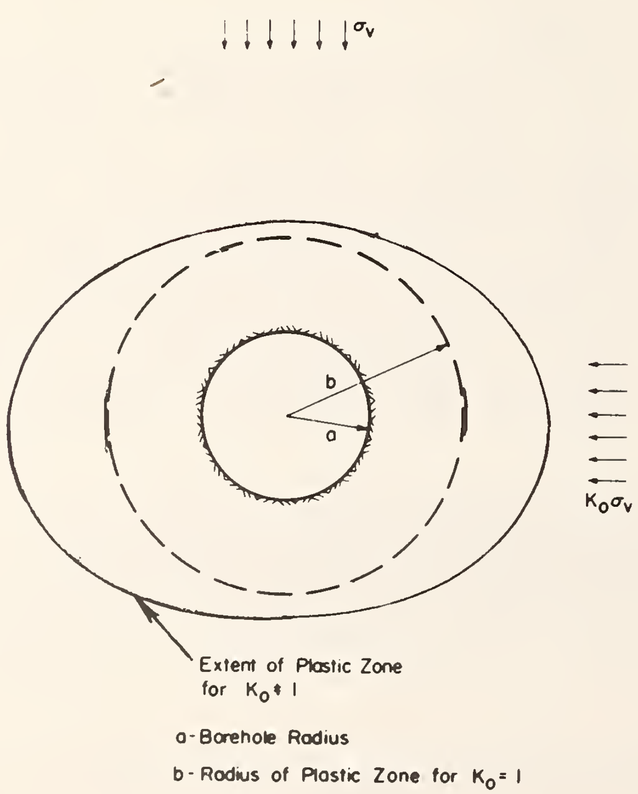


FIGURE I.2

QUALITATIVE SHAPE OF THE PLASTIC ZONE

Vertical boreholes in normally consolidated soil are subjected to all around equal stress, as the horizontal stress does not vary with direction. The formula upon which Figure H.6 is based (See Section H.4) will therefore apply exactly, provided the vertical stress σ_V is substituted by the horizontal stress σ_H. Typical values for σ_H in N.C. clay are 55* to 100** psf (2634—4790 N/m^2), which will lead to $(\sigma_H - p_i)/s_u$ ranging from 1 to 2.5. The plastic zone radius around vertical holes in cohesive soil will therefore typically range from 1 to 3 times the hole radius (from Figure H.6). In cohesionless soil below the groundwater table, $\bar{\sigma}_H$ will typically be $0.4\text{-}0.5\bar{\sigma}_V$. The plastic zone thus will be only half as deep as around horizontal holes (see Figure H.6) at the same depth if $K_o = 1$ for the horizontal case.

A comparison between the plastic zone around horizontal and vertical boreholes is presented in Figure I.3 for cohesionless and cohesive soil. Evidently the plastic zone is substantially larger around horizontal than vertical boreholes, and differently shaped. It is therefore likely that empirical correlations between measured values in vertical boreholes and the true in situ property cannot be applied unchanged to horizontal boreholes.

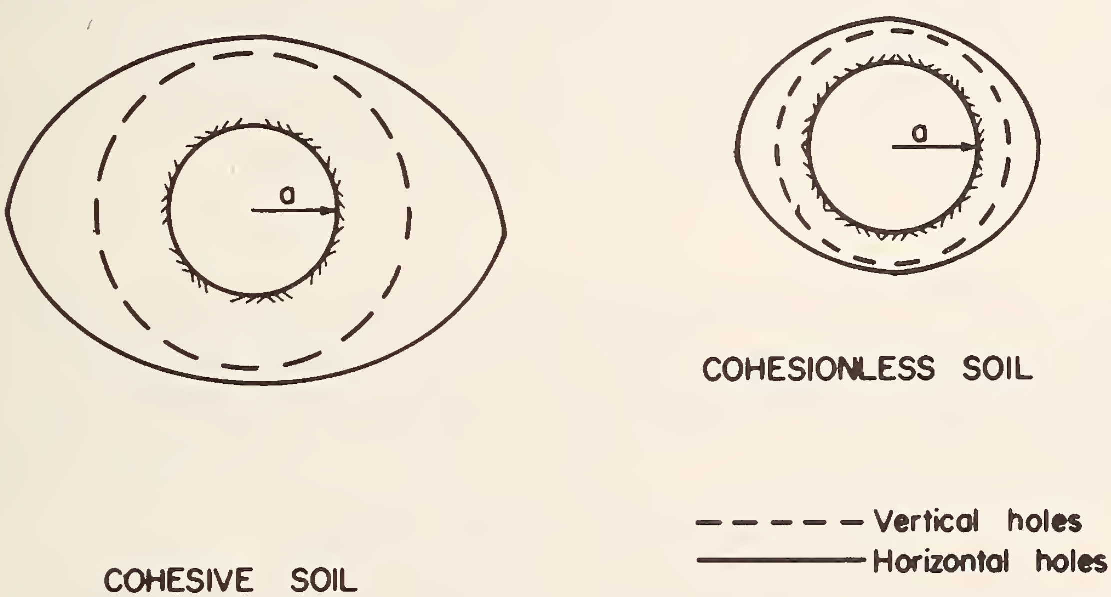


FIGURE I.3 EXTENT OF PLASTIC ZONE AROUND HORIZONTAL AND VERTICAL BOREHOLES

* Above GWT, $\sigma_H = \bar{\sigma}_H = K_o \bar{\sigma}_V \sim 0.5 \cdot 110 = 55$ psf

** Below GWT, $\sigma_H = \bar{\sigma}_H + u = K_o \cdot \bar{\sigma}_V + u \sim .6 \cdot 63 + 62.4 = 100$ psf

Deere et al (1969) give the radial displacement for an elastic medium around an opening to:

$$u_r = \frac{a}{2} \cdot \frac{\sigma_V}{E} (1 + \mu) \cdot 1 + K_o + (1 - K_o)(3 - 4\mu) \cos 2$$

where E = Young's Modulus, a is the radius and the other parameters are defined in Appendix H. The effect of an internal pressure in the opening can be subtracted from this value, and is equal to (for any K_o):

$$u_i = -p_i \cdot a \frac{1 + \mu}{E}$$

Deere et al (1969) also give formulas for deformation of elasto-plastic material, but they are too complicated to aid in drawing general conclusions. The diameter change necessary to develop a uniform pressure distribution around a tunnel is according to Peck et al (1972) in the order of 0.5%. Case studies reported by Deere et al (1969) for lined tunnels in soft ground show a linear distortion generally below 1%. Meaurements on the Washington Metro (Hansmire and Cording, 1972) show final displacements of the tunnel crown to be 13 in. or 5% of the tunnel diameter. A major part of this deformation can, however, be contributed to shield plowing and incomplete liner expansion.

Field measurements in horizontal boreholes are necessary to assess the deformations that will occur in different soil types. Evidence from tunnel case studies does, however, indicate that deformations leading to stability will be small, and not cause any hindrance to measurements in the borehole. Of course, conditions may arise (imbalanced mud pressure) which will result in hole collapse.

BOREHOLE FACE

Field measurements reported by Hansmire and Cording (1972) suggest that very limited deformations take place in front of the tunnel face for shallow horizontal holes. The deformations do not extend further than one radius from the face. It is therefore assumed that the soil disturbance in front of the borehole face is limited to one borehole radius, provided no erosion from impact of drilling mud occurs and a Δp is maintained.

I.4 DISTURBANCE EFFECT ON SOIL PROPERTIES

From the preceding discussion it is apparent that the excavation process may cause shallower disturbance in the soil around horizontal boreholes than the stress redistribution. Only drilling mud erosion of the face, hydraulic fracturing and crabbing can lead to disturbance beyond one radius depth. These factors will, however, probably be controlled as discussed in Section H.4. The character of the "mechanical" disturbance as drillbit rotation, anchor pad pressure, drill string buckling, etc., is such that the soil within one radius distance from the borehole probably is compacted and contains shear failures. This zone will then have undergone changes in shear strength,

density and pore pressure that will obscure the in situ values. Due to the erratic nature of the disturbance, it will probably not be possible to backfigure the undisturbed values. Measurements of the soil parameters will thus have to be taken outside this zone.

The development of yielding zones around the borehole will change both the strength and the stress-strain characteristics of the soils (for effects, see Ladd, 1971). Pore pressures will also change, but in cohesionless soil the pore pressure differences will dissipate fairly rapidly. This disturbed zone will extend to a depth of 1 to 7 times the borehole radius, and even further due to the difference in horizontal and vertical stress (See Figure I.2). It may be possible with experience and case studies in the future to backfigure the real in situ soil parameters. Experience from vertical holes can probably not aid in reaching this goal, as the extent of disturbance differs.

Disturbance due to the excavation process and the development of plastic zones require that all in situ measurements of soil parameters in horizontal boreholes have to be performed at least one radius and maybe several outside of the borehole wall. Only in front of the borehole face is the disturbance limited to one radius depth. Most mechanical measuring devices will thus have a very limited value in horizontal boreholes. Geophysical measurements extending far outside the disturbed zone will probably not be influenced by the disturbance.

APPENDIX J

EXPLORATION OF SUBSURFACE GEOMETRY WITH GEOPHYSICAL METHODS IN HORIZONTAL BOREHOLES

J.1 INTRODUCTION

Although the exploration approach is designed as an integrated system to provide the necessary information for a complete subsurface description, the separate exploration efforts can be assigned to one of two groups: (1) exploration of subsurface geometry, and (2) measurement of soil and water parameters in encountered strata.

Subsurface geometry denotes stratigraphy, bedrock surface and obstructions, which can be obtained with vertical borings, soundings or geophysical methods. Soil and water parameters are usually explored with contact testing in situ or determined from retrieved samples.

In connection with horizontal boreholes, geometry exploration will be a combination of contact sensing along the horizontal path and geophysical sensing at increasing radii from the drill path. Soil parameter exploration will mainly be accomplished by contact sensing. The surveillance of the excavation process (penetration rate, tailings, etc.) will give some additional information in both groups. This appendix describes exploration of subsurface geometry with geophysical methods in horizontal boreholes. Appendix K will describe contact sensing of soil and water parameters in horizontal boreholes.

J.2 GEOPHYSICAL EXPLORATION METHODS

Geophysical and indirect methods of subsurface exploration have been developed primarily by the petroleum and mining industries as tools for natural resource surveying. Use of this equipment in these industries has parallels to the needs of civil engineering. A review of the available geophysical methods was presented in two earlier D.O.T. research reports by Ash et al (1974) and Schmidt et al (1974). The following will therefore be restricted to brief comments on the various methods and their applicability in horizontal boreholes. Methods which fulfill the geometry exploration objectives meeting the size and compatibility constraints will be treated in depth.

Geophysical surveys utilize both active and passive measurement techniques. In an active mode, some form of energy is introduced into the earth, and the effect on the energy or the response of subsurface materials to energization is measured. Passive measurements record the strength of various existing force fields or changes in the strength of those fields.

Most geophysical methods are based upon changes of physical properties across boundaries. These physical properties influence the induced or existing force field. Measurement of these influences then yields information concerning both the physical properties and the boundaries. Some geophysical methods make spot measurements of physical properties (i.e. nuclear density log). However, it should be noted that almost all geophysical methods only indirectly measure soil parameters needed by the engineer. Shear wave velocity and damping are exceptions. However, geophysical methods are well suited for detecting boundaries (i.e. subsurface geometry) because the effects of these boundaries are directly measured.

Table J.1 presents a listing of the properties of the earth which can be directly measured by the various geophysical exploration methods.

TABLE J.1: PHYSICAL PROPERTIES UTILIZED FOR GEOPHYSICAL EXPLORATION

Number	Measured Property	Applies in Soil
1	Particle Acceleration, etc.	✓
2	Travel Times ($\approx$velocities)	✓
3	Magnetic Properties	✓
4	Temperature (t)	(✓)
5	Electric Resistivity (Ω) or	✓
6	Conductivity (S)	✓
7	Dielectric Constant (E_r)	✓
8	Moveable ions	✓
9	Radioactivity	(✓)
10	Absorption of radionuclides	✓

The geophysical exploration techniques available today can be divided into two general groups; surface methods and borehole methods. Table J.2 presents geophysical surface and borehole methods and the physical property they are primarily based upon.

J.3 ADAPTABILITY FOR HORIZONTAL BOREHOLES

To determine soil boundaries, bedrock and obstructions from horizontal boreholes, geophysical exploration systems must meet certain requirements. They must be compatible with the size of the boreholes (4½ to 12 in.) (11.4 to 30.5 cm) and the borehole environment (vibrations, noise, pressure, mud, etc.). The exploration system must also be able to fulfill the objectives of the exploration which are: (1) Detection of boulders and utilities in front of the borehole up to a distance of 100 ft (30.5 cm), (2) Mapping of boulders and utilities around the borehole up to a distance of 50 ft (15.25 cm), (3) Mapping of the bedrock surface, and (4) Mapping of soil stratification.

TABLE J.2: GEOPHYSICAL EXPLORATION METHODS

Letter	Surface Methods	Based on Physical Property*	Letter	Borehole Methods	Based on Physical Property*
a	Seismic refraction	2	m	Visual or photographic	-
b	Seismic reflection	2	n	Sonic	2
c	Electrical resistivity	5	o	Seismic	2
d	Magnetic	3	p	Spontaneous potential	5
e	Electromagnetic	6	q	Conventional resistivity	5
f	Gravimetric	1	r	Microresistivity	5
g	Radiometric	9	s	Focusing electrode	5
h	Acoustical holography	2	t	Induction	6
i	VIBROSEIS®	2	u	Electromagnetic Nuclear Response	8
j	DINOSEIS®	2	v	Gravimetric	1
k	Sonic	2	w	Thermometric	4
l	Nuclear	10	x	Gamma ray (natural)	9
			y	Gamma (emitted)	10
			z	Neutron (emitted)	10
			α	Acoustical Holography (AIM)	2
			β	Vibrating drill string	2

* See Table J.1 for definition.

Detection of obstructions in front of the borehole (in the following denoted "forward sensing") must be accomplished during excavation of the borehole. Thus compatibility between the excavation device and the exploration system is required for forward sensing. The three other objectives (denoted "all around sensing" in the following) can also be met by pulling the exploration system through the excavated borehole after removal of the excavation equipment. No limitations are imposed by the excavation equipment upon the "all around" sensors; however, borehole stability must be ensured (see Appendix H) to consider such a "follower package" for exploration.

The following presents a short description of the geophysical exploration methods from Table J.2, and their applicability to forward and all around sensing in horizontal boreholes. The conclusions concerning promising systems are based upon numerous interviews with the leading firms and practitioners in the geophysical field, and extensive review of recent literature (See List of References and Contributors). Further references and basic background information are given by Ash et al (1974) and Schmidt et al (1974).

a. SEISMIC REFRACTION. See "Seismic" in boreholes under (o).

b. SEISMIC REFLECTION. Same as (a).

c. ELECTRICAL RESISTIVITY. See "Conventional resistivity" in in boreholes under (g).

d. MAGNETIC. Measurements of variations in the earth's magnetic field intensity can indicate presence of magnetic material. Not applicable for exploration in urban areas because of non-uniform fields.

e. ELECTROMAGNETIC. Several so-called "earth probing radars" have recently been presented by different research groups (Cook, 1974; Moffat, 1974; Morey, 1974a). These systems are still in the development phase, at least for borehole adaptation. They might prove useful in the future if developed, but will have limited penetration below the groundwater table (few feet in clay) where most tunneling exploration is performed. One system has proven useful to locate boulders and utilities, the so-called "Electromagnetic Subsurface Profiling" (Morey and Harrington, 1972; Morey, 1974b). The inventor of the system has expressed confidence in redesigning it for use in boreholes larger than 4-5 in. (10.2-12.7 cm) diameter (Morey, 1975). The penetration is dependent on the soil conductivity and dielectric constant, and ranges from only 1-2 ft (0.3-0.6 m) in wet clay to 50-60 ft (15.2-18.3 m) in dry sand. The surveyed zone around a borehole would be shaped like a toroid, where directional determination is impossible. For forward sensing the "beam" would be funnel-shaped, and incapable of exploration just in front of the tunnel axis.

f. GRAVIMETRIC. Very sensitive instruments have been developed for the space industry (Buck, 1975). They are, however, large (24 in. diameter) (61 cm diameter), sensitive to vibrations and very expensive. More than $1 million was spent to develop the lunar gravimeter for the Apollo missions.

g. RADIOMETRIC. See "Gamma ray" in boreholes under (x).

h. ACOUSTICAL HOLOGRAPHY. See "Acoustical holography" in boreholes under (α).

i. VIBROSEIS®[1]. It is a useful surface system, but requires too large an energy source for borehole use (5-15 ton truck) (4536-13,608 kg truck) (Mossman et al, 1973). See "Vibrating drillstring" in boreholes under (β) for only likely borehole adaptation.

j. DINOSEIS®. See VIBROSEIS® above.

k. SONIC. See "Sonic" in boreholes under (n).

l. NUCLEAR. See "Gamma" and "Neutron" in boreholes under (y) and (z).

m. VISUAL OR PHOTOGRAPHIC. Useless for directly obtaining subsurface geometry, because of opaque drilling mud.

n. SONIC. Generation of elastic waves with high frequency acoustic energy sources (5 to 30 kH_z) for velocity logging of boreholes is called sonic logging. One example is the 3-D velocity log (Myung and Helander, 1973), which is not useful in soil due to the small velocity difference between saturated soil and drilling mud and the miniscule penetration distances. Sonic frequency ranges are generally associated with rock exploration.

o. SEISMIC. All seismic exploration techniques are based upon interpretation of travel time and path of elastic waves through the subsurface medium. Where the travel path is unknown or crosses boundaries of widely differing strata, the methods are heavily dependent upon <u>interpretation</u> and subject to error. Small seismic sources like air guns, sparkers and piezoelectric transducers are becoming available. No on-shelf exploration system exists for horizontal boreholes today, but development prospects seem good.

p. SPONTANEOUS POTENTIAL. The difference in potential between moving electrode in boreholes and fixed electrode on surface is measured.

q. CONVENTIONAL RESISTIVITY. Potential difference between two electrodes at fixed spacing within a borehole is measured. Penetration depth is up to half the electrode spacing, and resolution is limited to a tenth of the spacing at the best.

[1] Registered trade mark.

With several electrodes at different spacing over a large length, this approach might possibly be developed into a useful tool in horizontal boreholes in the future.

r. MICRORESISTIVITY. Penetration is limited to 6 in. (15.2 cm).

s. FOCUSING ELECTRODE. Penetration of measurable potential is limited to a few feet.

t. INDUCTION. Conductivity difference is measured at a maximum distance of 10 ft (3.1 m) from the borehole.

u. ELECTROMAGNETIC NUCLEAR RESPONSE. The secondary electromagnetic field from moveable water ions in the soil is measured. This response can be applied to measure in situ permeability, however both development and experience are needed for adaption to horizontal boreholes.

v. GRAVIMETRIC. See "Gravimetric" on surface under (f). Borehole tools not rugged, and lack necessary sensitivity to detect boulders and utilities.

w. THERMOMETRIC. No measurable temperature differences exist in soil between boulders and the soil matrix or differing strata.

x. GAMMA RAY (NATURAL). Penetration is limited to a few inches.

y. GAMMA (EMITTED). Same as (x) above.

z. NEUTRON (EMITTED). Same as (x) above.

α. ACOUSTICAL HOLOGRAPHY (AIM). Holographic display of elastic waves to obtain 3-dimensional image of the interior of solid bodies has been presented as a "revolutionary" exploration method. Holosonics (1970) and Price (1974) describe a technique called "Acoustical Imaging," the present predecessor of acoustical holography. The penetration in rock is limited to 30-100 ft (9.2-30.5 m). With the high operation frequencies (8 and 22 kH_z), the penetration in soil would only be a few feet. A major research effort is presently (1975) underway in Norway to employ holography for 3-dimensional display of data on a large scale from offshore seismic exploration. Although seismic holography is still in the early development stage, a potential for future use in exploration of subsurface geometry can be anticipated.

β. VIBRATING DRILLSTRING. Generation of elastic waves by vibrating the drillstring in a borehole is a seismic technique, but deserves special attention due to its unique energy source. CONOCO (Waters, 1974) employed a "jar" (springloaded weight normally employed to free jammed drill pipe) to introduce impact shocks in the face of vertical boreholes. That research

program was abandoned, as seismic waves were generated both by the drill bit and the drill string, and thus interpretation of the travel path of the received surface signals was impossible. CONOCO is presently working on a new research program, employing vibrating drillstrings in horizontal holes as signal sources for exploration of coal seams. At a frequency of 2 kH_z, the effective range is 200-300 ft (61-91.5 m) in coal. No reflections have so far been recorded in the borehole containing the source. In December, 1974, it was estimated that "more than one year" is necessary for full equipment development.

From the preceding listing it is obvious that no system is available for forward and all around sensing in horizontal boreholes today. Some promising concepts and systems in development were found, as the vibrating drillstring, acoustical imageing (AIM), electromagnetic earth radars, conventional resistivity and various seismic methods. Only the seismic methods have basic components compatible with the borehole constraints and technology advanced enough to provide a forward and all around sensing system within reasonable time and cost limits. The following section will therefore discuss seismic exploration in soil, the physical relationships and packaging of forward and all around exploration systems for horizontal boreholes.

J.4 SEISMIC/ACOUSTIC EXPLORATION

Many of the geophysical exploration methods in Table J.2 are based upon measuring time intervals, assuming a travel path, and calculating propagation velocities and geometric attitudes of reflectors and refractors. All the different names, such as seismic refraction and reflection, acoustical holography, VIBROSEIS®, DINOSEIS®, sonic and vibration drillstring, just reflect differences in generation of the waves and methodology of the interpretation of the measured velocity. The basic physical laws are the same, and apply for all the methods.

Propagation of seismic and acoustic waves in soil differs considerably from that of elastic waves in an ideal, homogeneous, isotropic and linear elastic solid. Soil is a three-phase medium, consisting of soil grains, pore fluid, and pore gases. So in addition to geometrical spreading, wave energy is dissipated by intergranular friction (damping). This damping leads to high decay rates (attenuation) of waves in soil as compared with e.g. rock. Thus the wave propagation is limited, and as higher frequencies attenuate faster, the resolution is poor. (Resolution is a measure of how small an object can be detected at a given distance.)

Seismic and acoustic sensing are differentiated only by frequency of the source signal. Seismic signals range from approximately $0.01H_z$ to 100 to $400H_z$. Acoustic signals range from $400H_z$ to $30,000H_z$. The signals propagate by the same physical mechanism. Because of differences in source types, acoustic signals are more monochromatic and

seismic signals more random or polychromatic (have a wide frequency range). See J.11 for the frequency distribution of a seismic signal source.

The sources considered in this discussion emit polychromatic signals; however, discussion pertaining to attenuation should not change whether one treats mono or polychromatic signals. Unfortunately, there is so little comparative attenuation data for any signal type that no substantial conclusion can be drawn for differences in attenuation.

Traditional seismic work from the surface is performed along a line, and yields information in two dimensions (horizontal distance and depth). Forward and all-around sensing from a horizontal borehole is three-dimensional. The geometry and definitions of terms for forward and all-around sensing are presented in Figure J.1. All exploration in front of the plane perpendicular to the borehole axis at the face is defined as forward sensing. Radial exploration from the borehole is defined as all-around sensing. Seismic waves generated by the energy sources propagate as spherical waves in a homogeneous medium. The waves will be refracted and reflected at boundaries between materials with different wave velocities. Examples of reflection and refraction paths are drawn on Figure J.1.

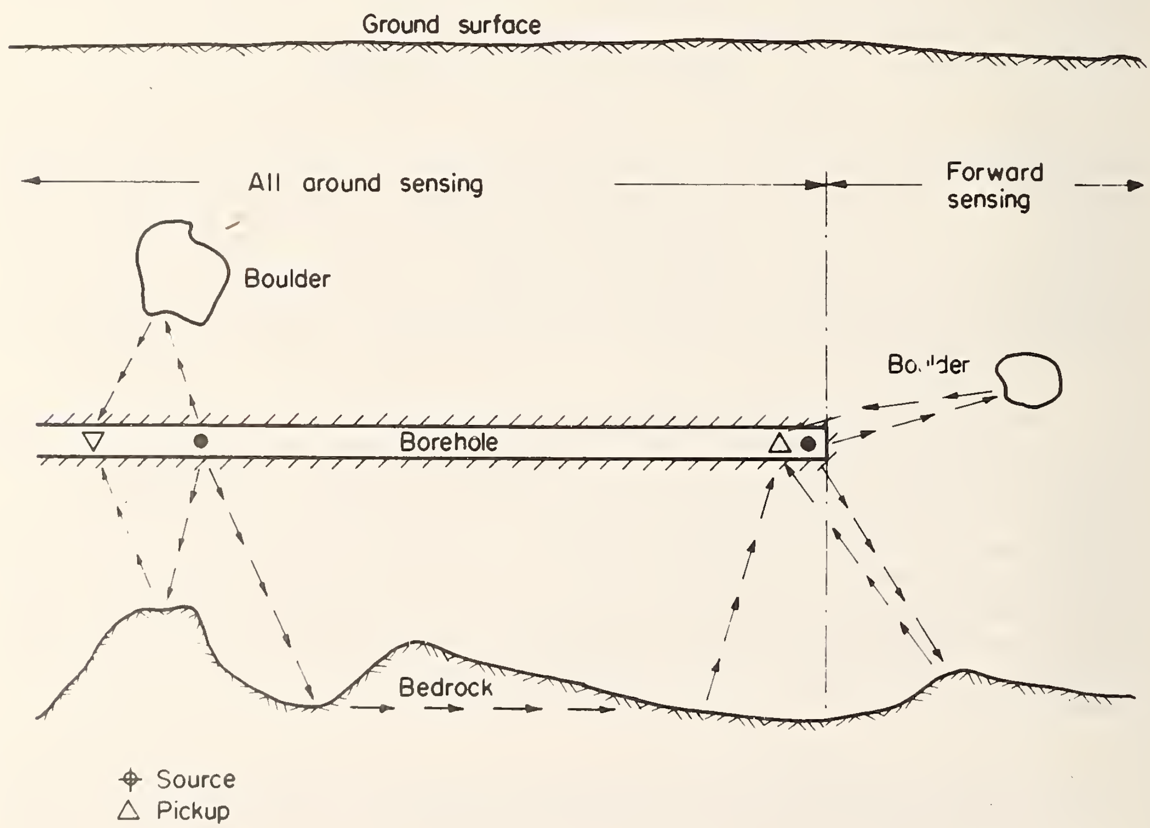


FIGURE J.1 SEISMIC EXPLORATION FROM HORIZONTAL BOREHOLES (SCHEMATIC)

In order to evaluate the sensing capability of a seismic system (range, resolution), the following system parameters must be known: (1) Frequency characteristics of energy source, (2) Amount of energy coupled to the ground, (3) Attenuation of seismic waves, (4) Energy loss by reflection or refraction, (5) Pick-up sensitivity, and (6) Background noise level in borehole and recording equipment.

SEISMIC WAVES IN SOFT GROUND

A recent DOT report (Rubin et al, 1974) presents a fairly thorough treatment of acoustic or seismic waves in soil, which in the following is assumed as background information.

Seismic waves are characterized by frequency and velocity, and have the wavelength

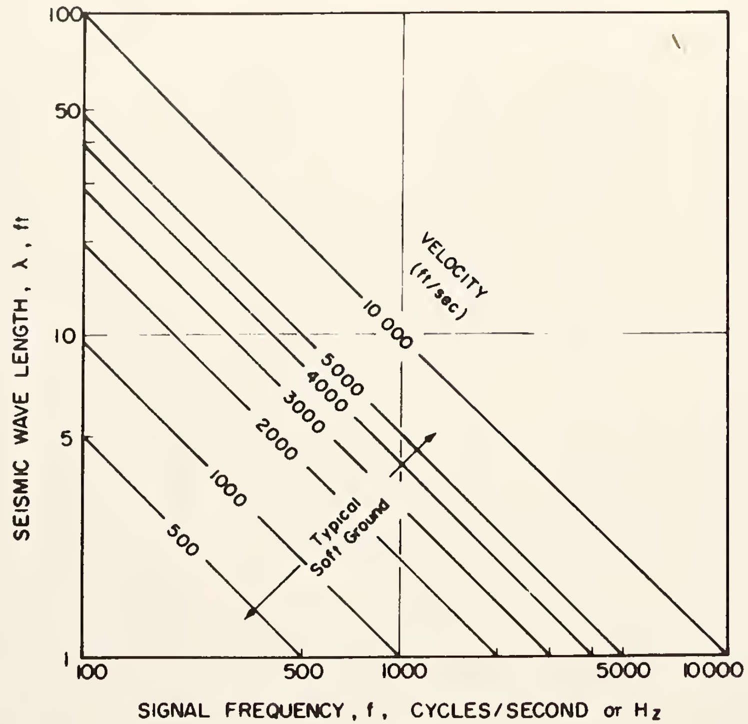
$$\lambda = \frac{V}{f} \text{ (ft or m)}$$

where: V = seismic wave velocity (ft/sec or m/sec) and f = frequency (sec^{-1}). Figure J.2 presents a plot of this relationship.

The size object which will reflect significant amounts of seismic energy (a measure of the reflection technique's ability to "see" or resolve the size of objects, hence resolution) can be assumed equal to one wavelength. Better resolution might be obtained, but higher energy loss occurs by reflection if the reflecting object is smaller than one wavelength. See Kuster (1972) for theoretical treatment. Higher frequencies will therefore enable detection of smaller-sized objects in a medium with a given seismic wave velocity.

Unfortunately, high frequency seismic signals are not a unique solution to exploration in soft ground because the attenuation increases with frequency. One of the interpretations of attenuation of dilational waves (P-waves) in Pierre Shale is shown in Figure J.3. These results, preesented in terms of decibels, dB, indicated a linear relationship between frequency and attenuation up to 600 H_z. A decibel (dB) = 20 $\log_{10} P_0/P_1$, where P_0 is the initial amplitude and P_1 is the final amplitude, or dB = 10 $\log_{10} E_0/E_1$, where E_0 is the initial energy and E_1 is the final energy. Measurements of P-waves in silty clay by U. S. Army Corps of Engineers Waterways Experiment Station (WES) (Weiss, 1974) indicate the same type of relationship (See Figures J.4 and J.6). So with increasing frequency the penetration decreases (<u>assuming that the same maximum wave amplitude is generated at all frequencies</u>).

The high attenuation characteristics of the soil thus force one to choose between high frequency to see small objects and low frequency to obtain large penetration. An optimal seismic exploration system should therefore emit waves ranging from low to high frequencies to assure best possible resolution at any distance. Figure J.5 gives, qualitatively, the implications of the frequency dependent attenuation. As the distance away from the borehole increases, the size of the smallest detectable obstacle (boulder) increases.



(1 ft. - 0.305 m)

FIGURE J.2 SEISMIC WAVE LENGTH VS. FREQUENCY (After Schmidt et al., 1974)

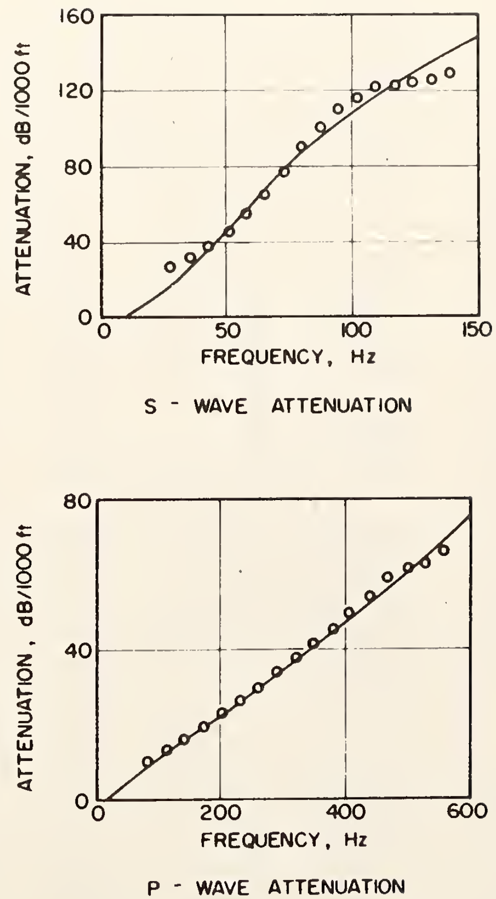
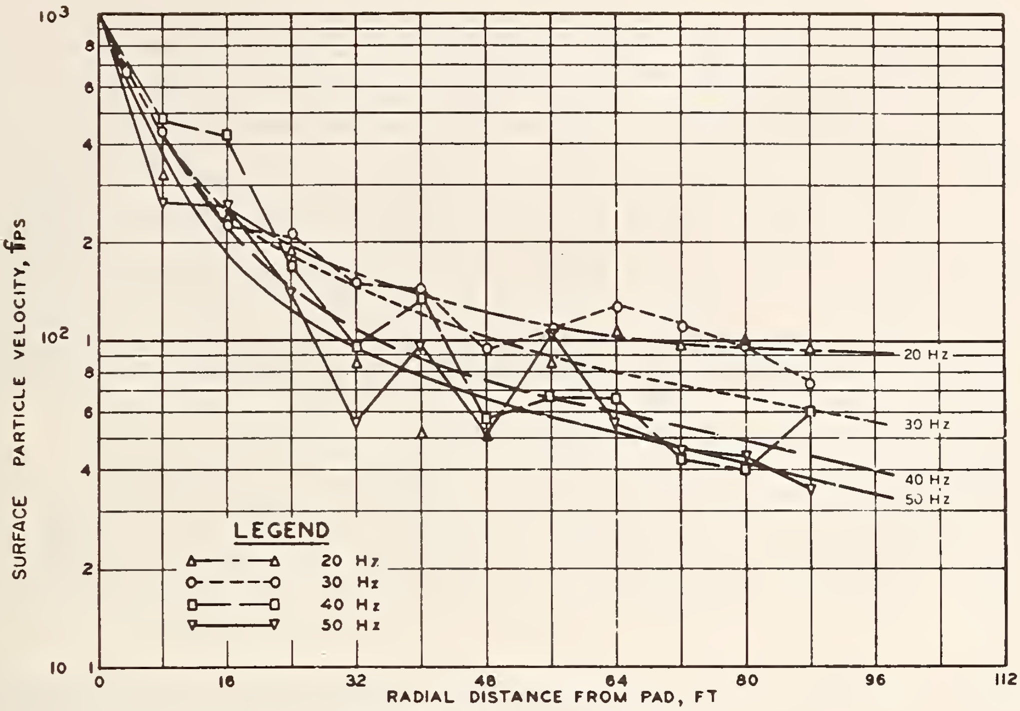
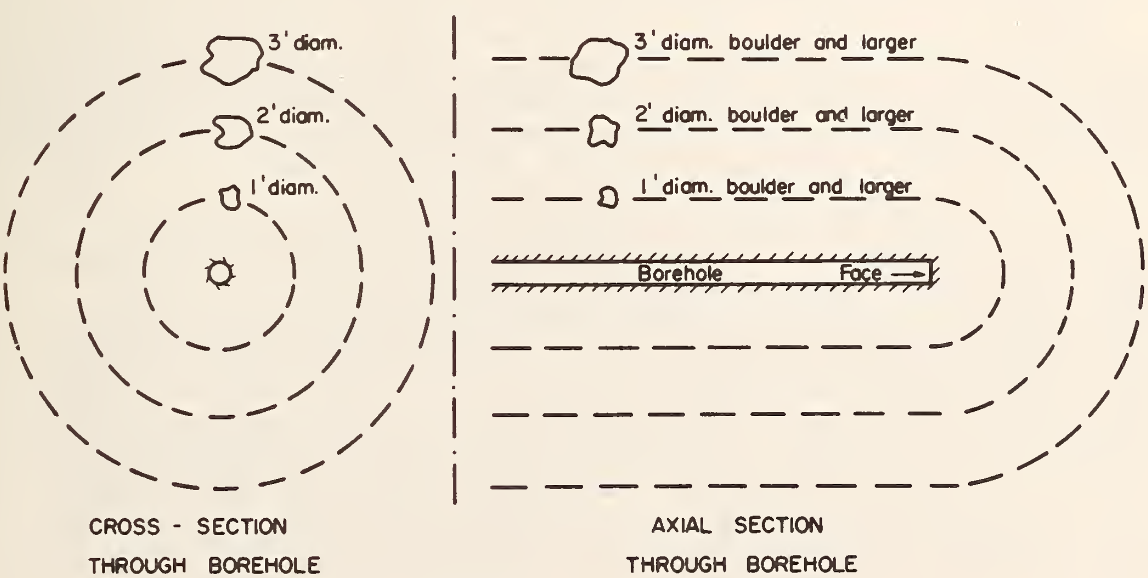


FIGURE J.3 SEISMIC WAVE ATTENUATION IN PIERRE SHALE (From Rubin et al., 1974 after McDonald et al., 1958)



(fps = 0.305 m/s; 1 ft. = 0.305 m)

FIGURE J.4 PARTICLE VELOCITY ATTENUATION CURVES NORMALIZED TO 1000 IPS (After Weiss, 1974)



(1 ft. = 0.305 m)

FIGURE J.5 QUALITATIVE CONTOURS OF DISTANCES TO MINIMUM DETECTABLE BOULDER SIZE

P-wave propagation velocity in normally consolidated soils varies with depth and saturation. Above the ground water table, the velocity ranges from approximately 1000 to 2000 ft/sec (305 to 610 m/sec); whereas below the ground water table, the P-wave velocity is approximately 5000 to 5500 ft/sec (1525 to 1675 m/sec), practically the same as for water. The P-waves at a certain frequency will therefore be shorter above the ground water table than below, and hence resolution may be better. However, the attenuation for P-waves is much higher above the ground water table, so the decrease in the penetration distance will offset the increase in resolution. The final result is that a certain size object can be located further away below rather than above the ground water table. This conclusion is ver ified by the following discussion.

All the velocities from the WES study were measured under the same test conditions. A vibratory oscillator on a concrete pad resting on the soil surface generated the seismic waves. Pick-ups were placed on the surface and in refilled boreholes down to 35 ft (11 m) depth. The boreholes were located on radial lines extending from the pads. Data in Figure J.6 represent attenuation of through transmission waves.

The wet, clayey, silty soil at the WES testing site (P-wave velocity $V_P \simeq 5000$ ft/sec indicates an amplitude reduction of 75% per wavelength travelled (12 dB). The dry, sandy soil at the Eglin test site (P-wave velocity $V_P \simeq 1350$ ft/sec) indicates an amplitude reduction of 88% per wavelength (18 dB). The attenuation for only the first half of the wavelength formed the basis for these values, which yield attenuation values on the low side. Measurements of shear wave attenuation by Brown (1974) in saturated silty sand averaged 65% amplitude reduction over 12 ft (3.6 m) between 35 and 50 ft (10.7 and 15.2 m) depth.

Table J.3 presents a summary of the available attenuation data for soft ground. More data to complete this table will be available from Waterways Experiment Station and Shannon & Wilson in late 1975. The table is based on the assumption that the decibel ratio attenuates linearly with both frequency and length of travel path.

These attenuation data are employed to plot minimum obstacle (boulder) size that can be detected at various distances from the borehole. As given by Rubin et al (1974), the useable amplitude ratio (amplitude sent/amplitude received) for seismic exploration could be as high as 10,000:1 or 80 dB. This 80 dB value stems from an elastic limit of the input displacement of $3.3 \cdot 10^{-4}$ ft (10^{-4} m), to the seismic background noise level of $3.3 \cdot 10^{-8}$ ft (10^{-8} m). It is further assumed reflection off a boulder with diameter equal to one wavelength results in a loss of half the amplitude 6 dB (Toksoz, 1974). As the wave must travel to the boulder and back, maximum sensing distance is governed by the available amplitude ratio A_R corresponding to ½ (80-6) dB = ($P_0/P_1 = 70.8$), and will be:

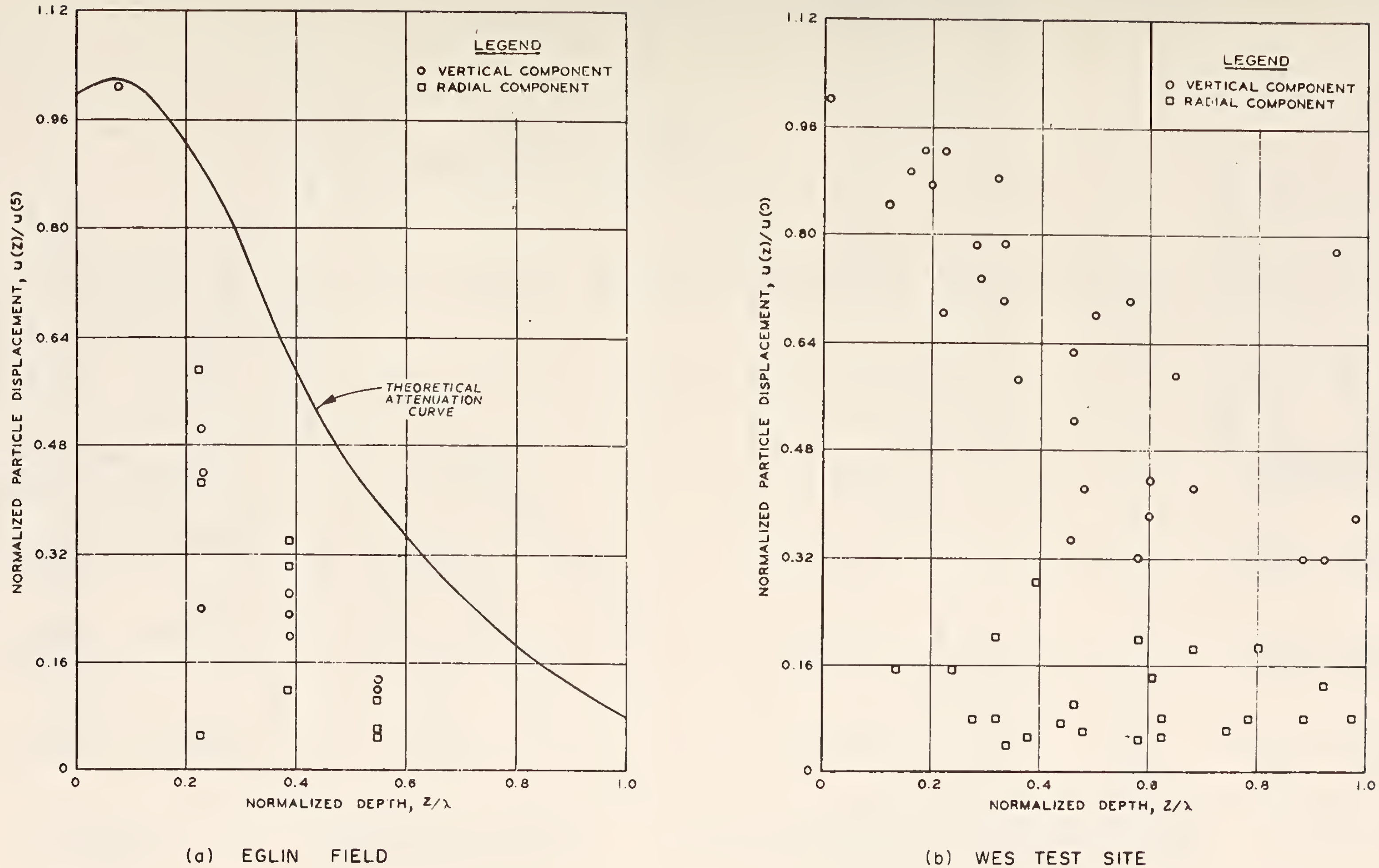


FIGURE J.6 ATTENUATION OF PARTICLE DISPLACEMENT WITH DEPTH
(After Weiss, 1974)

TABLE J.3: ATTENUATION DATA

Test Description	Propagation Velocity V (ft/sec)	Attenuation** Factor k' (dB/ft·H_z)	Energy Loss (dB) Per Wavelength	Reference
Saturated soil, S-wave	2000	.0039	7.8	Brown (1974)
Wet soil, WES, P-wave	5000*	.0024	12	Weiss (1974)
Dry soil, Eglin, P-wave	1350	.0135	18	Weiss (1974)
Pierre shale, P-wave	6750*	.00012	.8	McDonald et al (1958)

* Estimated values

** The attenuation factor is a constant indicating how much wave energy is lost per unit distance and frequency.

(1 ft. = 0.305 m)

$$L_{max} = \frac{A_R}{k'f}$$

where: k' = Attenuation factor (dB/ft Hz);

f = Frequency (Hz);

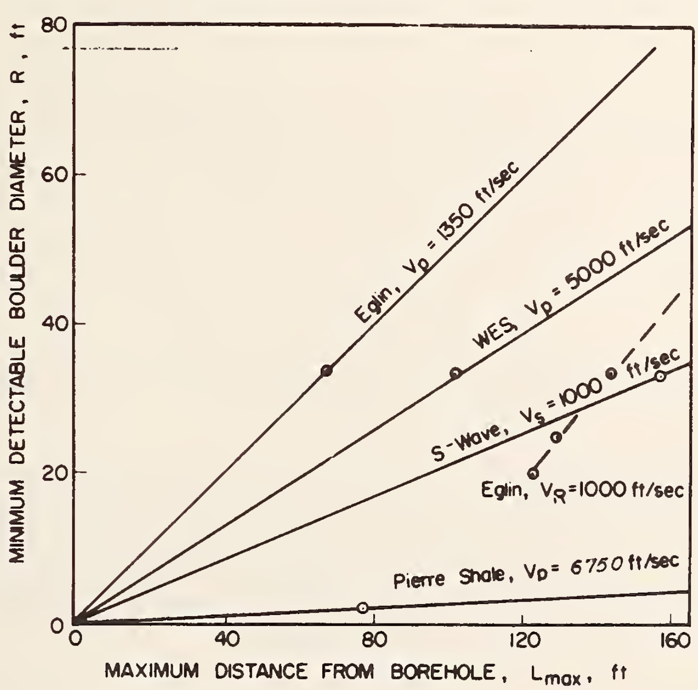
L_{max} = Maximum sensing distance (ft);

A_R = Amplitude ratio (dB).

The minimum boulder diameter detectable at this distance is

$$R = \lambda = \frac{V}{f} \text{ (ft)}$$

Figure J.7 presents boulder diameter versus distance from borehole for the available attenuation data and previously noted assumptions, which are: (1) Soft ground is isotropic w.r.t. seismic wave velocity, (2) The seismic energy source is capable of coupling enough energy into the ground for 80 dB available attenuation at a very wide frequency band, (3) The background noise level is low enough to permit a detectable signal after 80 dB attenuation, (4) Half the wave energy



(1 ft. = 0.305 m)

FIGURE J.7 MINIMUM DETECTABLE BOULDER SIZE VS. DISTANCE FROM BOREHOLE

(amplitude) is lost by reflection, (5) The resolution is one wavelength ($R = \lambda$), (6) Estimated wave velocities (see Table J.3) are correct, and (7) The attenuation data are correct.

Example Calculation at Eglin Test Site:

If $V_p = 1350$ ft/sec

$A_R = 37$ dB

$k' = .0135$ dB/ft H_z (Table J.3) and

$f = 40\ H_z$

then $L_{max} = \frac{A_R}{k'f} = 68.5$ ft (20.9 m) and

$R = \lambda = \frac{V_p}{f} = 33.7$ ft (10.3 m).

This relationship is linear with respect to distance due to the assumed constant attenuation factor k' (.0135 dB/ft Hz).

Example Calculation for WES Surface Measurement:

If $V_R = 1000$ ft/sec

$A_R = 37$ dB

$f = 50$ Hz and

$k'f\ (\alpha) = .33$ dB/ft

(The attenuation factor, Figure J.4, is not linear with distance. Hence k'f was chosen for a distance of 100 ft);

then $L_{max} = \frac{A_R}{k'f} = \frac{A_R}{\alpha} = 123$ ft (37.5 m) and

$R = \lambda = \frac{V_R}{f} = 20$ ft (6.1 m).

Remember that a given resolution, e.g. 20 ft, requires a wavelength of 20 ft. The frequency of this wave will vary from soil type to soil type, dependent on the wave velocity.

The necessary assumptions for Figure J.7 are all unconservative, so the resolutions will very likely be poorer than Figure J.7 indicates. The background noise level in the borehole will very likely exceed $3.3 \cdot 10^{-8}$ ft (10^{-8} m), at least during drilling and when operating in a typical urban environment. The wide frequency band assumed can probably not be provided by any single energy source.

SEISMIC ENERGY SOURCES

The single most important criteria for selecting energy sources for seismic exploration of soft ground from horizontal boreholes are size and compatibility. Due to the difference in these criteria between forward sensing and all around sensing, the two will be discussed separately.

Forward Sensing

For forward sensing the source can only be placed on the drill bit. If placed behind the motor and navigation package, the travel distance for the seismic waves will be too long and the excavation equipment will interfere with the signals. This interference results from the multiple travel paths of the seismic waves that are possible. If the left seismic source on Figure J.1 should be employed for forward sensing, waves could travel along the excavation equipment, in the drilling mud and in the soil. It would thus be difficult to determine which forward travel path corresponded to a measured wave travel time.

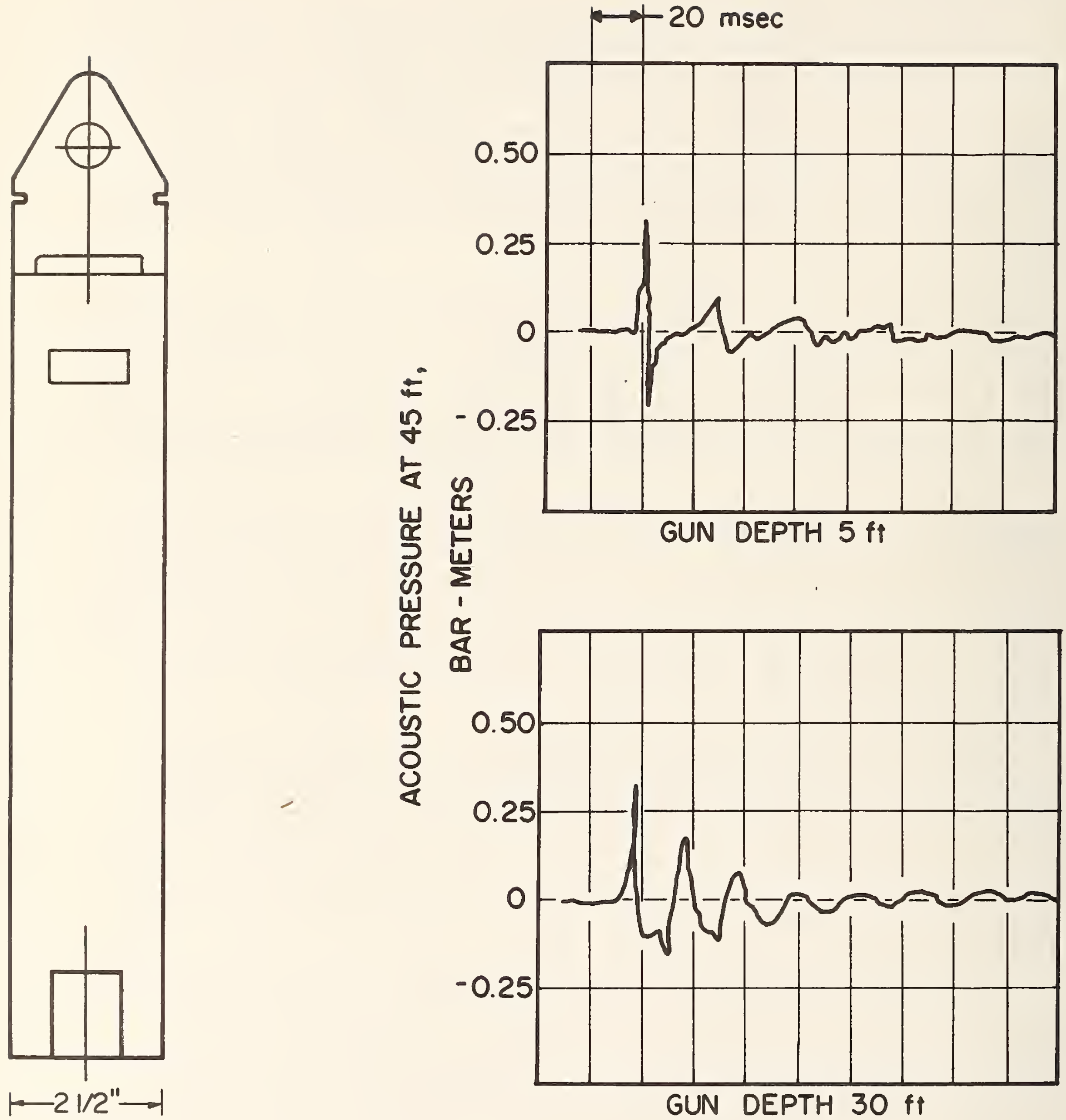
The 4½ in. (11.4 cm) diameter drill hole cannot accommodate a source on the bit, thus forward sensing is impossible in this size hole. For the 7 in. (17.8 cm) hole, a drill bit with 2 in. (5.1 cm) diameter coring opening can be furnished. This modular space is around 8 in. (20.3 cm) long, and can be made available for a seismic energy source. The 12 in. (30.5 cm) diameter drill bit makes an even larger modular space possible.

Another criterion for a suitable energy source is a large frequency bandwidth, so the smallest possible obstacle is detected at the largest distance from the borehole. As an example, an energy source emitting only waves at, say, 150 Hz in soil with a P-wave velocity of 5000 ft/s (1525 m/s) will not detect obstacles smaller than 33 ft (10 m) in diameter due to the poor resolution. If the energy source is operated only at 5000 Hz, the smallest detectable obstacle would be 1 ft (0.3 m), however, maximum penetration is then less than 3 ft (1 m).

Desired penetration is 50 ft (15 m) for all around sensing and 100 ft (30 m) for forward sensing. Below the groundwater table (V_p=5000 ft/sec) a minimum frequency of 150 Hz is thus required for 100 ft (30.5 m) penetration of forward sensing (from Figure J.7). In dry soil (V_p=1350 ft/sec) a frequency of 27 Hz gives the same penetration. Detection of boulders down to 1 ft (0.3 m) diameter is desired, which requires an upper frequency limit of 5000 Hz in wet soil and 1350 Hz in dry soil (where V_p=1350 ft/sec).

To summarize: the seismic energy source for forward sensing in a horizontal 7 in. (17.8 cm) diameter borehole is limited to 2 in. (5.1 cm) diameter, and should have a frequency range from 27 to 1350 Hz in dry soil (V_p=1350 ft/sec) and 150 to 5000 Hz in wet soil. Three different sources which might meet these requirements are:
The PAR® air gun produced by Bolt Associates, Inc., the sparker produced by Bolt, Beranek and Newman, Inc., and the sparker produced by Teledyne Exploration.

The PAR® air gun is 15 3/4 in. (40 cm) long and has a diameter of 2 1/2 in. (6.4 cm) (See Figure J.8). It is not likely that the air gun can be produced in smaller sizes, so it will only fit the 12 in. (30.5 cm) diameter drill bit. The frequency characteristics in a borehole are not yet exactly known, but will probably range from 50 Hz upwards. Output signatures obtained in water with the air gun (Figure J.8) indicate



(1 in. = 2.54 cm, 1 ft. = 0.305 m)

FIGURE J.8 PAR® AIR GUN AND OUTPUT SIGNATURE
(After Bolt, 1974)

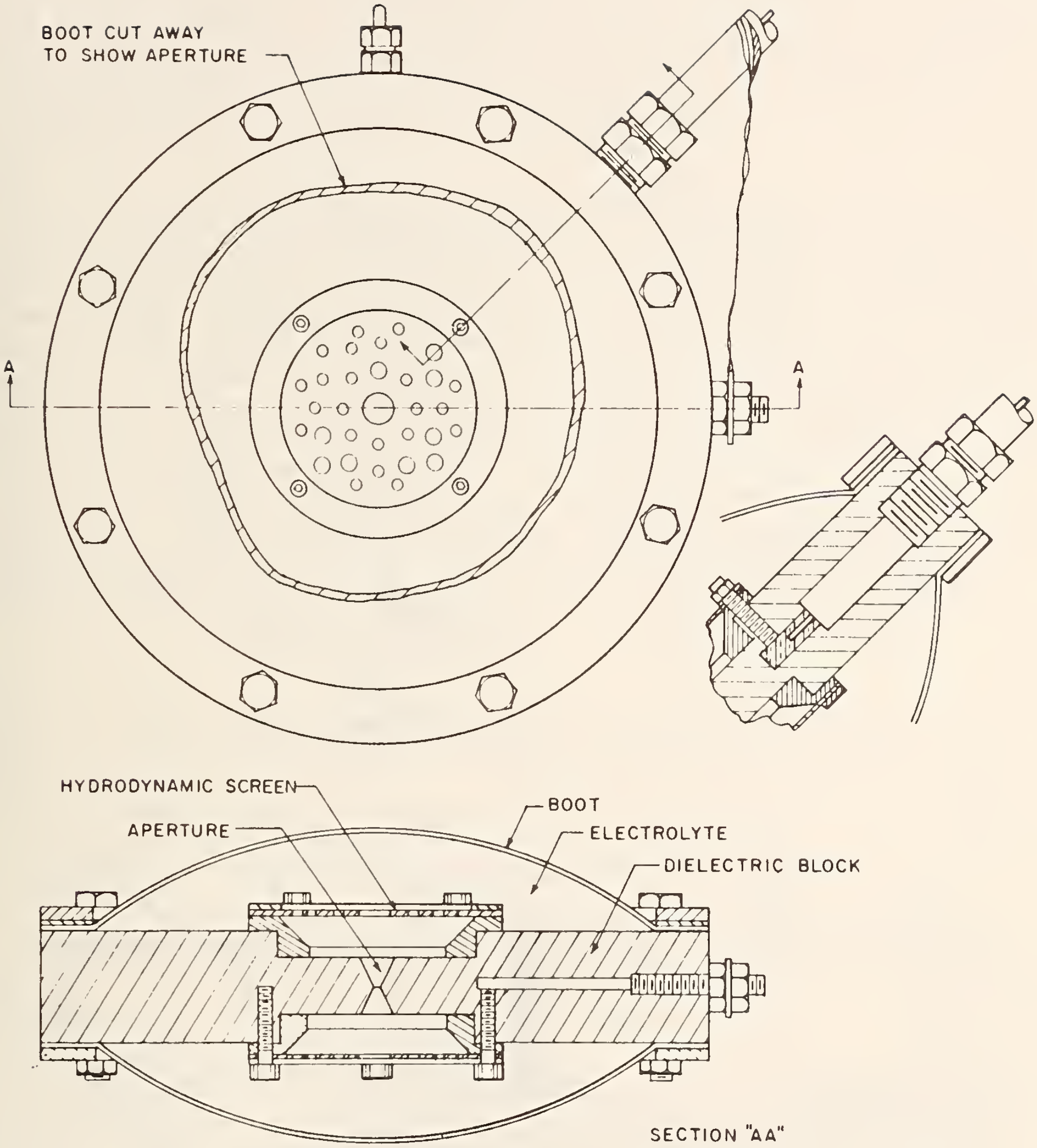


FIGURE J.9 DOUBLE - BOOTED ELECTRODELESS SPARK DEVICE (After Wright, 1975)

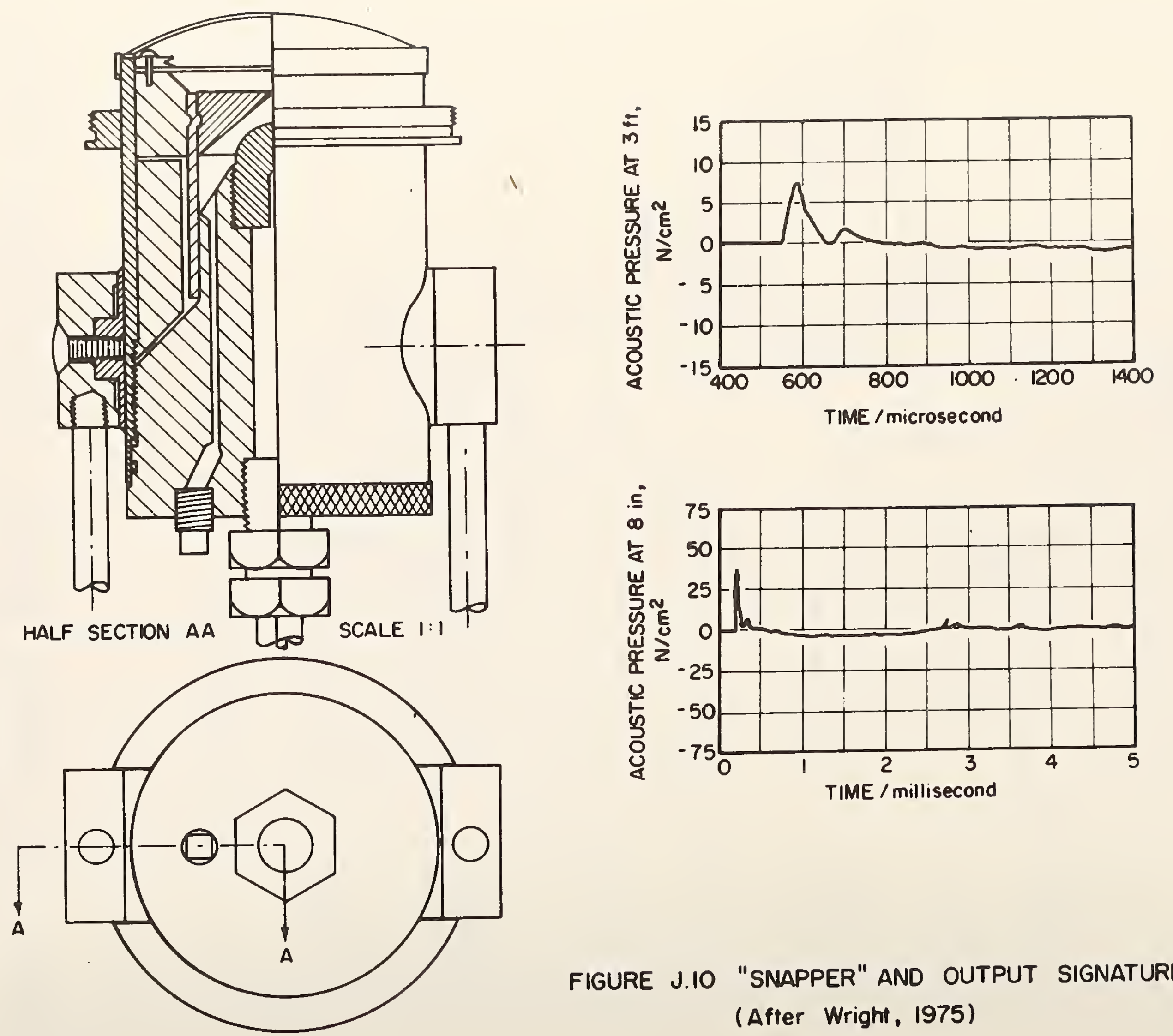


FIGURE J.10 "SNAPPER" AND OUTPUT SIGNATURE
(After Wright, 1975)

that the air bubble oscillates at approximately 20 ms intervals for more than 100 m sec. Thus reflected signals could be buried in this "after-noise," and the gun may not be suitable for forward reflection sensing. This is very important. Any seismic source considered for reflection survey in soil has to have a short and sharp pulse, so the reflections do not arrive at the pick-up before the outgoing pulse has passed. Filtering might help somewhat to ease this problem, but adds to the complexity of the equipment.

Bolt, Beranek and Newman has built several sparkers in different sizes and shapes (See Figures J.9 and J.10). The following data refers to the 2½ in. (6.4 cm) diameter, 5 in. (12.7 cm) long cylindrical sparker called "snapper" in Figure J.11. The useable frequency bandwidth is about 150 to 8000 Hz (See Figure J.11), however, at increasing depth and pressure in the borehole, some of the low frequency energy will be lost. The rarefaction period (noise following main pulse due to spark bubble collapse) is about 3 microseconds. The snapper generates a 60 microsecond compression pulse, so no cavitation will occur at the membrane, and good coupling with the drilling mud will be ensured (See Figure J.10). Increasing borehole pressure would depress the rarefaction pulse and thus limit the low frequencies and the penetration distance. Figure J.10 is recorded under 1.5 atmospheres pressure.

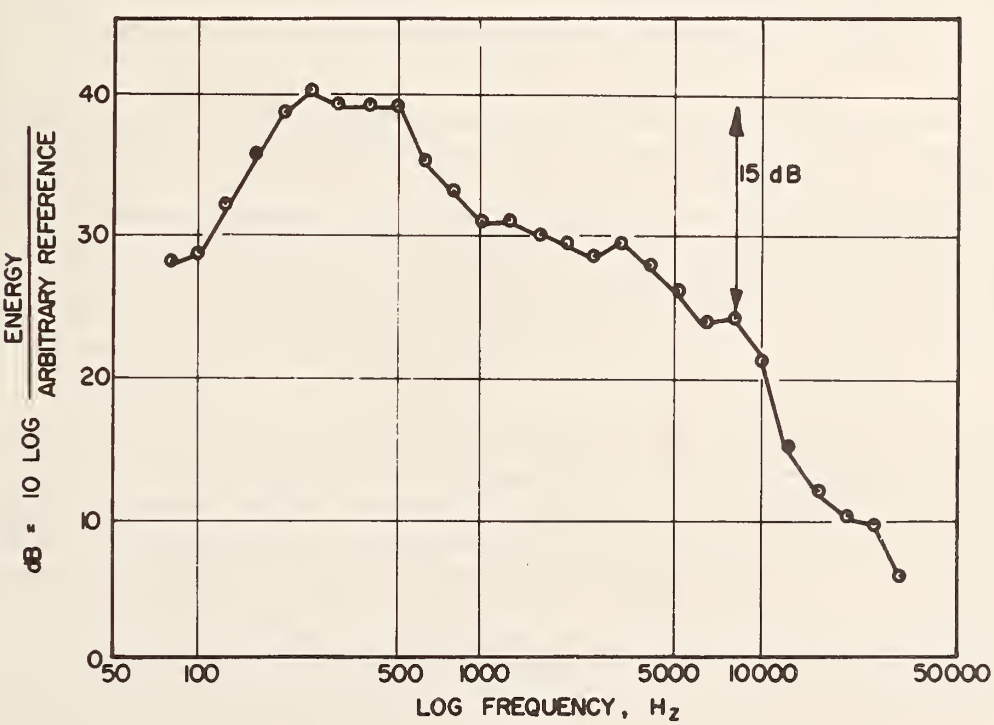


FIGURE J.11 FREQUENCY CONTENT OF SPARK DEVICE ("SNAPPER")
(After Wright, 1975)

Teledyne Exploration produces sparkers 1½, 2 and 2½ in. (3.8, 5.1, and 6.4 cm) in diameter, with a frequency range of 400 to 800 Hz and 2 millisecond rarefaction period. These sparkers will experience too short penetration and poor resolution in soil, and are therefore less applicable for forward sensing. However, no output signature is available for the sparkers, so the frequency range might possibly be better than quoted above.

To summarize; the factor limiting seismic exploration in soft ground is wave attenuation. The attenuation of P-waves seems to be linear with frequency, and high frequency waves are attenuated much faster than low frequency waves. This implies a rapid loss of resolution as the distance from the borehole increases (See Figure J.6). Based on WES data from Figure J.7, a one-foot boulder can only be "seen" the nearest 2-3 ft (0.6-0.9 m) from the borehole; at a distance of 30 ft (10 m) the smallest detectable boulder is 10 ft (3 m) in diameter.

All Around Sensing

All around sensing does not impose as strict size limitations on the energy source as forward sensing does. Less required penetration leads to a desired frequency range of 300-5000 Hz in wet soil and 54-1350 Hz in dry soil. Both the PAR® air gun (Figure J.8) and the double-booted sparker in Figure J.9 would seem suitable regarding size constraints and performance requirements. The air gun may be less suited for high resolution reflection surveys, but, due to lower frequencies, ideal for refraction surveys.

To summarize this section on seismic energy sources, it can be said that an optimum energy source for exploration from a horizontal borehole would have a frequency range from 25 to 5000 Hz. Ideally the source should operate both at one swept frequency (25-5000 Hz) and at selective frequencies (e.g. at 25, 50, 100, 500 and 5000 Hz). The selective frequencies would reduce scattering (less reflections) and thus decrease the number of received signals. Rubin et al (1974) proposed a chirp signal to facilitate better filtering of uncorrelated noise. However borehole sized chirp sources need to be developed.

To enable these "advanced" features of the energy sources, piezoelectric transducers will probably have to be utilized. Until they are more fully developed, however, only the air gun and the sparker appear to fulfill the frequency, size and compatability requirements of seismic energy sources. They do not offer a controllable frequency range, but they have been built and tested and therefore represent systems with a low enough component cost to be economically attractive. It can be anticipated that once a market exists for sophisticated borehole seismic sources, piezoelectric sources in small size delivering high energy will be developed and built.

DESIGN OF SEISMIC EXPLORATION SYSTEM FOR FORWARD SENSING

The cylindrical sparker (snapper) appears to be a suitable source for forward sensing in saturated soft ground. The shaded area in Figure J.12 represents the exploration capabilities of this source. Within a minimum distance (~7 ft in wet soil and 2 ft in dry soil) the reflections have to be picked up through the rarefaction noise. The inclined limitation of the exploration capability reflects P-wave attenuation from Figure J.7. The maximum sensing distance is governed by the wave velocity and the minimum output frequency of the source. This source's penetration appears to be 14 ft (4m) in dry soil. In saturated soil, it appears to be 100 ft (31 m).

For forward sensing, the energy source is placed in the modular space on the drill bit. Placed on the bit sub or motor (1 ft behind the bit) is one omnidirectional hydrophone. The distance between the source and the pick-up is for all practical purposes negligible. With the source as a center, the limiting boundaries for penetration at different frequencies will be spherical. Distances to reflecting objects can be calculated from wave arrival time.

Even though the seismic energy source is accommodated in the drill bit, the compatibility problems are not solved. For the air gun, high pressure air tube and a firing cable has to be passed from the surface to the source. For the snapper an electric cable is necessary. Rotation of the drill bit makes this connection difficult. The problems associated with connecting a rotating part with a non-rotating part will be discussed in detail in Appendix K in connection with the forward sensing piezometer cone. The pick-up on the bit sub (which also is rotating) may be moved somewhat further back and placed on a non-rotating part of the excavation equipment to omit slip-ring problems.

When minimum arrival time is measured for a certain reflection, it can be assumed that the reflecting object is located perpendicular to the borehole axis. The range along the borehole path where a certain reflection is registered can be employed to calculate approximately the size of the reflecting object (See Figure J.13).

It must, however, be noted that only size and distance from borehole can be measured. The location of the reflecting object on the circle around the borehole is unknown, as shown in Figure J.13. A set of directional pick-ups around the bit sub could solve this problem. However, if the exploration hole is drilled along the central axis of a future circular tunnel, only the radial distances to the obstructions are of concern, and not where they are located on the circle.

If two or more boulders are located near each other, the distinction between them will probably be impossible, and the simple method in Figure J.13 to determine size and distance might not apply. Also if the bedrock is near the borehole, reflected waves from the bedrock will very likely obscure any boulder reflections. Cross-shooting between

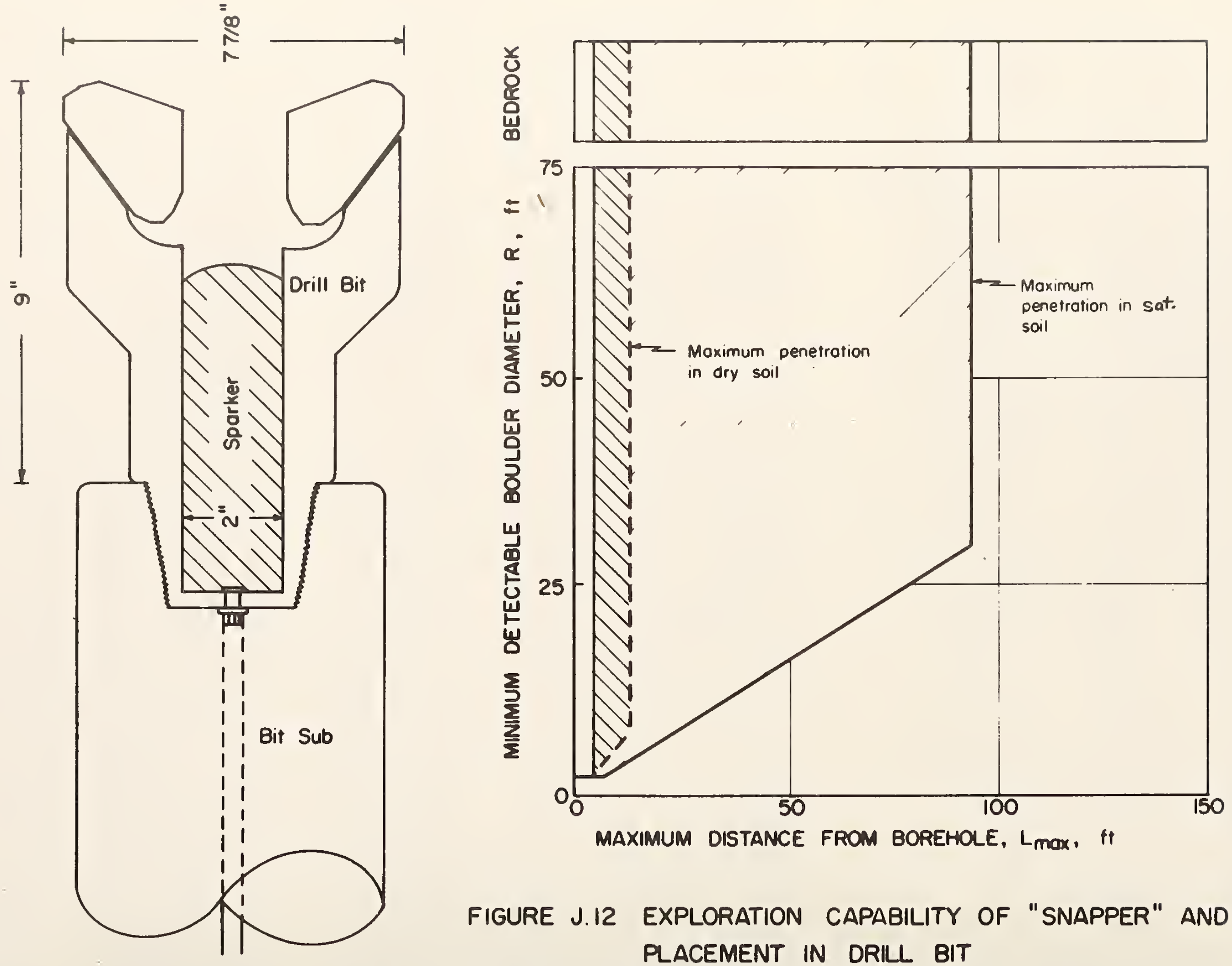


FIGURE J.12 EXPLORATION CAPABILITY OF "SNAPPER" AND PLACEMENT IN DRILL BIT

(1 in. = 2.54 cm; 1 ft. = 0.305 m)

two boreholes might help solve some of these problems, but is not found cost-effective due to the limited additional information and high extra costs.

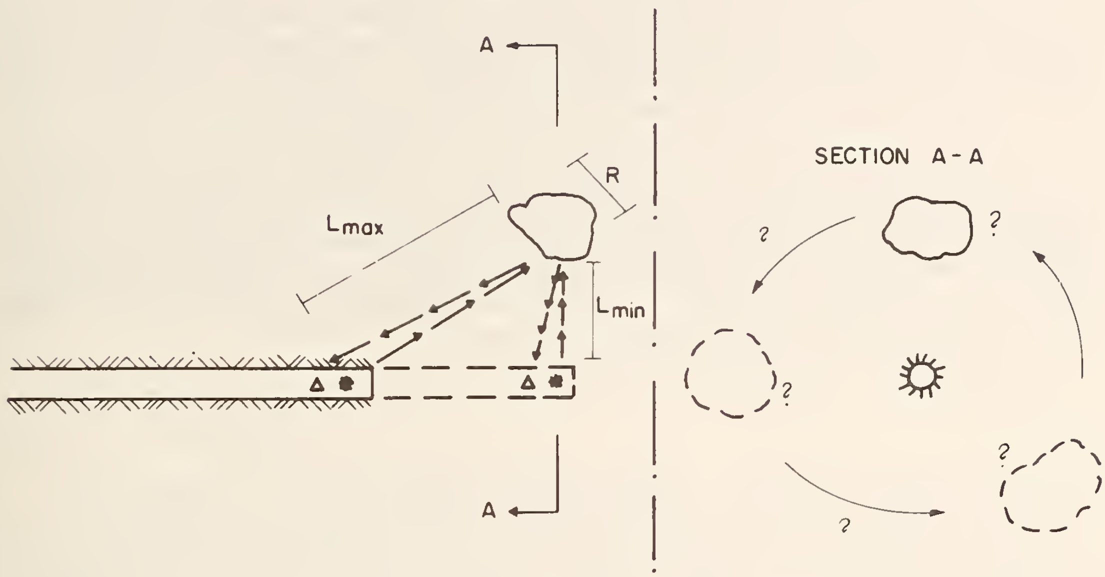


FIGURE J. 13 DETERMINATION OF LOCATION AND SIZE OF REFLECTING OBJECT

DESIGN OF SEISMIC EXPLORATION SYSTEM FOR ALL AROUND SENSING

All around sensing can be performed either during excavation, or after the excavation is completed. Provided stability of the borehole is assured, all around sensing is preferably performed in a previously excavated hole. No interference with the excavation equipment can then occur, and more time will be available for exploration, as no drilling operation has to be shut down for the geophysical survey.

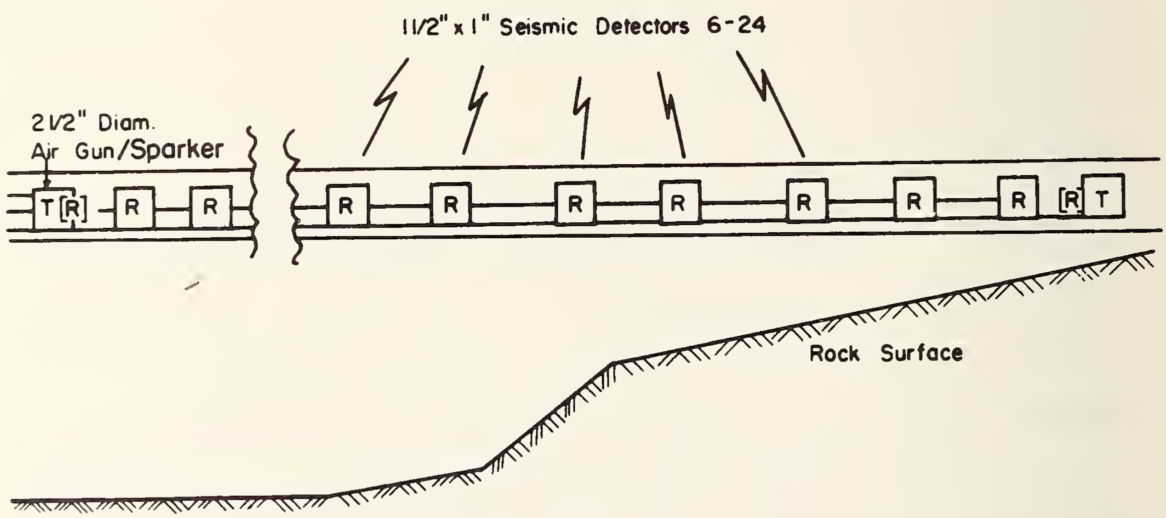
All around exploration during excavation with the mandrel system is judged not feasible for two reasons: (1) The steel drill string will provide a high velocity path for the generated waves and obscure the reflected and refracted signals, and (2) Energy sources and pick-ups attached to the drill string will be vulnerable to destruction during handling and excavation.

Exploration during excavation with the thrust applicator is feasible. Energy sources and streamer cables can be built into the umbilical cable of the thrust applicator or pulled through an excavated

hole. Therefore the following will consider only exploration in a completed borehole without interference with the excavation equipment.

Figure J.12 presents the radial sensing capabilities of the snapper in saturated soil ($V_p \simeq 5000$ ft/sec, 1520 m/sec). The shaded area represents where reflections from boulders can be obtained. The exclusion of the 6 ft (1.8 m) nearest to the borehole represents the duration of the rarefaction pulse. As previously noted, it might very well be possible to filter the reflections from the rarefaction pulse. However, this will require field testing to be conclusively proven.

For refraction survey of the bedrock surface, the most suitable energy source will be the PAR© air gun, presented in Figure J.8. As shown in Figure J.14 the sources would be placed at each end of an array of detectors or streamer cable. In present systems the air hose is approximately ½ in. (1.3 cm) in diameter, and one hose would be sufficient for the two energy sources (Bolt, 1975).



(1 in. = 2.54 cm)

FIGURE J.14 SEISMIC PROFILING SYSTEM FOR ALL AROUND SENSING

The blocks designated at "R" are seismic detectors and it appears that a minimum of 6 to as many as 24 can be utilized in a horizontal borehole system. All detectors are connected through a multiconductor cable of approximately 1/4 to 3/8 in. (0.6 to 1 cm) diameter, depending on the size or possible absence of a stress core. The conducting wires are obviously very small, with one pair going to each detector; Number 26 wire is the usual size for standard seismic exploration cables. All cables and detectors are placed inside an oil-filled vinyl tube, 1½ in. (3.8 cm) diameter. Such streamer cables are readily available (e.g. from Teledyne), but will normally contain too many detectors (typically around one hundred), so a special order must be made.

The total length of the system will depend on the distance to bedrock and the relative velocity difference between bedrock and the overlying soil. For the required 50 ft (15.2 m) penetration, the total length of the system will have to be about 200 ft (61 m).

With regard to on-surface recording, both analogue and digital means are recommended.

If immediate decisions by a nontechnical machine operator have to be made regarding the depth to a rock surface (or a probability of a rock surface) being encountered with continued driving of the device, it appears that a set of nomograms could be made available to him wherein he can, by immediate inspection, determine the depth to the rock surface. That would appear to be the most economical method of field operation.

On the other hand, if complete computer analysis of data were required, then a unit occupying the space of a small delivery truck would probably suffice for immediate processing and graphic printout of the rock surface profile. The foregoing applies, of course, to refraction profiling. In the event that the results of reflection profiling were suitable, then a direct analogue recording would allow the machine operator to have a continuous graphic record of the depth to the rock surface, much as the operator of a boat has a continuous record of the water depth beneath him by observing a continuous recording fathometer.

With further regard to the on-surface instrumentation and space requirements, it should be noted that if analogue refraction and/or reflection techniques are the selected methods, then minimal space requirements will result. Most of the on-shelf, presently available instrumentation is suitcase size for this type of geophysical operation.

The problem of distinguishing wave arrivals, that is, returning energy from a rock surface directly beneath the tunneling device as opposed to a rock surface that is shallowing to either side of the device, can possibly be resolved by the use of directional detectors; wherein, the polarity of the received signal would indicate that the energy is

coming from directly below or left or right of the detector. Therefore, a three-component detector rather than single component might have to be utilized in the seismic profiling system. The feasibility of three component detectors does, however, depend on a known orientation of the streamer cable. Unsymmetric weighting of the streamer might be the easiest solution to that problem. This streamer cable would be about 2 in. (5.1 cm) in diameter, as the three-component detector is 1½ in. (3.8 cm) in diameter.

Arraying of sources that can be fired in a synchronized manner to facilitate generation of planar waves have been considered. Due to the high attenuation, this does not seem feasible.

It should be emphasized that if a reflection survey is made for forward sensing, no radial reflection survey is necessary. If the forward sensing system is capable of mapping the bedrock, a refraction survey would mainly provide wave velocity data. However, if the hole is stable, a refraction survey to verify the reflection data may be a wise allocation of funds.

APPENDIX K

SOIL AND WATER PARAMETERS IN HORIZONTAL BOREHOLES

K.1 INTRODUCTION

The introduction in Appendix J surveyed exploration for tunnel design and construction and explained the division of the subsurface exploration into geometry exploration and measurement of soil and water parameters. This Appendix discusses contact testing methods to obtain soil and water parameters from horizontal boreholes. The feasibility of possible exploration methods will be judged on the basis of compatibility with the borehole environment, the influence of borehole stability and the size of the disturbed zone around the borehole.

K.2 INFORMATION FROM EXCAVATION PROCESS

Monitoring the penetration of the soil with the excavation equipment can yield information both about the subsurface strata and some geotechnical parameters. The following data could be recorded during excavation without stopping: (1) Penetration rate, (2) Normal force on drill bit, (3) Torque on drill bit, (4) Tailings (returned drilling mud with excavated cuttings), (5) Load-deformation curves from the anchor pads on the thrust applicator.

The rate of penetration can be directly measured on the surface by keeping track of time and corresponding cable or drill pipe length entering the borehole. Penetration data will yield qualitative information about relative density and stiffness of the encountered strata provided bit wear is not excessive. A very careful logging of the whole drilling operation is strongly recommended, not only to obtain more information about the equipment capabilities, but also to reach some conclusions about "drillability" or "problem soils" in the encountered strata.

The normal force on the drill bit will also yield information about relative density and stiffness of the strata. In addition the normal force measurements will enable determination of bit contact with the soil, or the extent of jetting by the drilling fluid. This information can in turn be utilized to decide whether to activate the dump valve (see Appendix I, Figure I.1).

Normal force would be ideally measured by mounting a strain gauge or load cell (e.g. vibrating wire) on the bit or the bit sub. The parts are, however, rotating, so unless other instruments are mounted on the drill bit (e.g. a seismic source and pick-up), the solution might not be cost-effective. A better alternative would be construction of a load cell in the sub directly behind the motor. This load cell will have to

be calibrated to account for reaction torque from the rotating drill bit. For the thrust applicator system, a normal pressure transducer in the applicable range (Tyco, 1975) can be mounted on the hydraulic valving system (See Figure K.1) to measure the pressure in the axial extension cylinder and thus the thrust on the bit.

Exxon Drilling Research (Ledgerwood, 1975) built a sub to measure time variation of thrust and torque on drill bits about 10 years ago. It was to be placed between the drill bit and the drill collars, and contained a tape recorder for data acquisition. The sub was 8 in. (20 cm) in diameter and about 20 ft (6 m) long, so a major redesign would be necessary to utilize the device in horizontal drilling.

The torque on the drill bit will be directly proportional to the mud pressure drop in a positive displacement motor. This drop can be conveniently measured by one pressure transducer on each side of the motor (See Figure K.1). The Tyco transducers are about 1 in. (2.5 cm) in diameter and 1 in. (2.5 cm) long, so they would not cause compatibility problems. Where an electric motor is used, the torque can be obtained from consumption of electric energy.

Returning drilling mud should be vibro-screened and hydro-cycloned to remove cuttings before reuse of the mud. From examining the cuttings, soil type (gravel, sand, silt, or clay) and changes in soil type can be determined. Depending on the annulus volume and penetration rate versus mud flow rate, the appearance of cuttings on the surface will lag behind the excavation of these cuttings by some calculable amount.

The load-deformation curves from the anchor pads on the thrust applicator may yield information about strength and deformability of the soil around the borehole. As discussed in Appendix I, a substantial zone around the borehole might be disturbed or even plastified. Therefore, the information from the anchor pads is questionable, and may be regarded more qualitative than quantitative. Load on the pads can be monitored by a pressure transducer on the hydraulic valving system for the pads (See Figure K.1). The deformation can be measured by monitoring the amount of fluid going into the thruster to extend the anchor pads. However, since downhole valving systems vent into the drilling system, measurement of the flow volume cannot employ monitoring of mercury slugs. The slugs would be vented.

Additional information, such as the pressure distribution in the mud circulation system downhole, can easily be achieved by spacing pressure transducers along the excavation system. This information might prove useful to find the right drilling mud composition, and prevent hydraulic fracturing of the borehole wall.

K.3 CONTACT TESTING IN HORIZONTAL BOREHOLES

The specific drawings and pertinent data inventory of in situ contact testing methods employed in vertical boreholes were discussed by Schmidt et al (1974). This section will be restricted to a

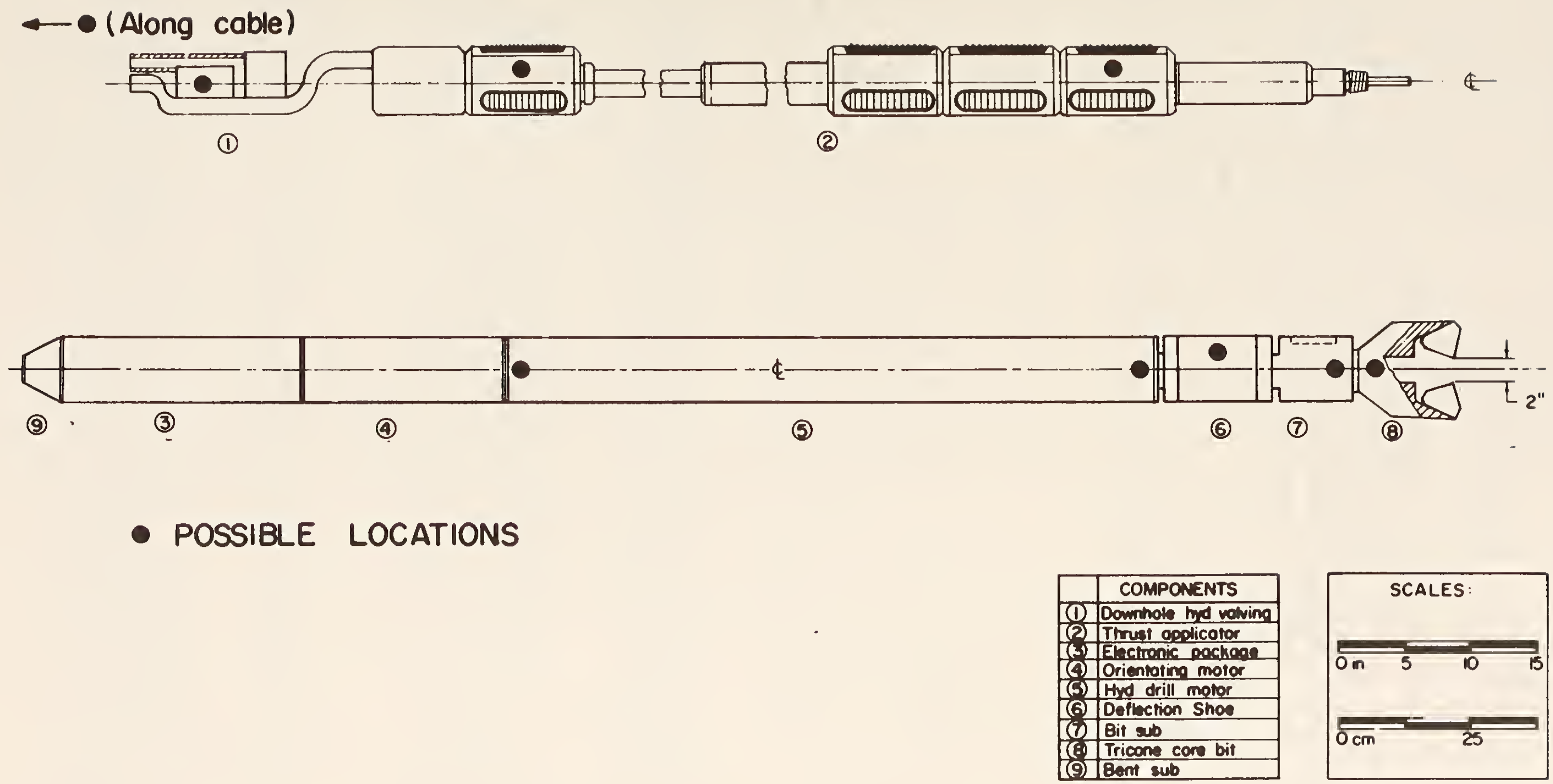


FIGURE K.1 PRESSURE TRANSDUCER LOCATIONS

brief description of the various methods, and their applicability to horizontal boreholes. In addition, three innovative instruments will be introduced; a downhole vane, a piezometer cone placed on the drill bit to measure pore pressure and penetration resistance, and a caliper survey to determine borehole stand-up time.

STANDARD PENETRATION TEST. Compatibility with the borehole excavation equipment and the horizontal orientation of the borehole rules out the standard penetration test. A spring-loaded device to stimulate a 140 pound (63 kg) hammer falling 30 in. (76 cm) would be necessary, as would a retrieval system to clean out the spoon.

DYNAMIC CONE PENETRATION TEST. See standard penetration test.

STATIC CONE PENETRATION TEST. The idea is combined with the piezometer cone, which is a combination of static cone penetrometer and piezometer.

VANE SHEAR TEST. Shannon & Wilson (Hancock, 1975) built a wire-line operated vane device with McClelland, which is only 3 in. (7.6 cm) in diameter and 10 ft (3 m) long. This would not fit on the drill bit, but could probably be modified so that it may be operated from a package to the rear of the motor. A stiff rod placed in a hole drilled through the motor center (only possible with the Nichols motor) could extend and retract the vane blades in the drill bit. Substantial hardware development would then be necessary, which is at this time judged infeasible due to a lack of indices for horizontal vane tests (which correction factor should be used?) and the alternative usage of the modular space on the bit. A vane or a static cone might be pushed into the soil perpendicular to the borehole with some telescopic system. The disturbed zone around the borehole and the anticipated hardware development problems, however, rule out this possibility.

DILATOMETER TEST. Dilatometers or pressuremeters expand the borehole wall radially. Dilatometers are used mainly in research in the U. S., due to difficulties in the interpretation of the resulting pressure-deformation curves. In horizontal boreholes the interpretation will be even more difficult than in vertical holes, due to the larger disturbance around the hole (See Appendix I and Figure I.3).

BOREHOLE JACK TEST. Unidirectional load is applied to the borehole wall via curved loading plates in the borehole jack test. The same limitations and conclusion as stated for the dilatometer applies here also.

IOWA BOREHOLE SHEAR TEST. This test is performed by pulling two curved, rough plates anchored against the borehole wall, thereby shearing the soil. It is limited by the same disturbance problem discussed above for dilatometers.

PIEZOMETERS. An advanced piezometer type will be described below under piezometer cone.

BOREHOLE PERMEABILITY TEST. This test is not applicable in horizontal boreholes that are stabilized with drilling mud. The filter cake prevents pumped water from filtering into the soil formation. If water is pumped out of the formation, borehole stability may be lost.

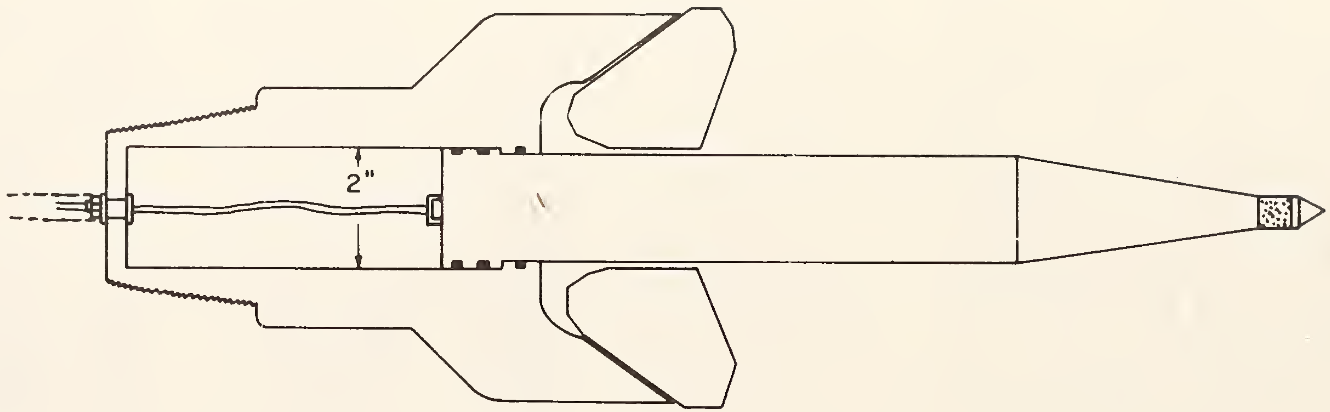
PIEZOMETER CONE. The cone-shaped piezometer is a newly developed tool that has the ability to measure soil permeability, relative density or "stiffness" of soil and pore water pressure (Wissa et al, 1974). It can be fit into the modular space on the 7 7/8 in. (20 cm) diameter drill bit. Figure K.2a shows the cone fully extended in the bit. Figure K.2b presents a cross-section of the piezometer cone, which is 16 in. (40 cm) long and 2 in. (5 cm) in diameter. The porous tip reaches then about one drill bit diameter into the soil. In Section H.3 the disturbance in front of the borehole face was found to be on the order of one radius, therefore the piezometer cone will penetrate through the zone of maximum disturbance.

CALIPER. The caliper is an instrument designed to log diameter variations in boreholes. It has four to six extendable arms that are springloaded against the borehole wall. For horizontal borehole use the caliper would have to be somehwat modified with supports to keep it approximately centered in the borehole. The caliper is not compatible with the excavation device without major redesign, and will therefore be discussed as a follower package in Section K.4.

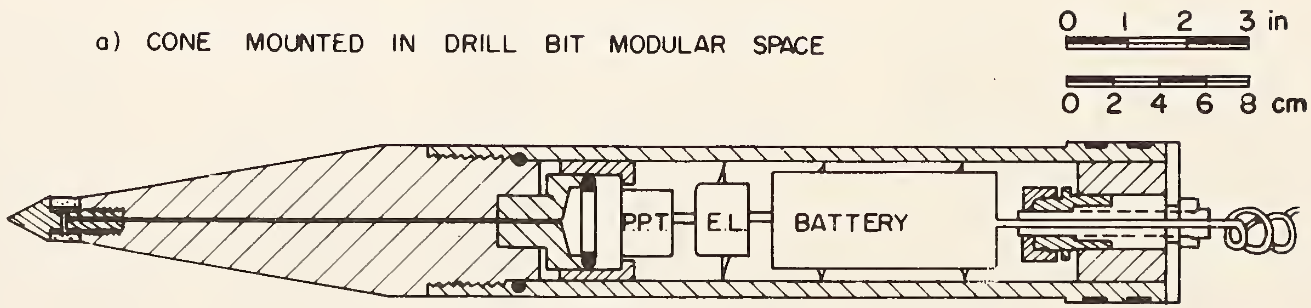
The preceding discussion has shown that only two of the contact sensing devices are promising for use in horizontal boreholes, the piezometer cone and the caliper. The recording capabilities of the cone and excavation system compatibility are discussed below.

The placement of the piezometer cone in the drill bit is advantageous, due to the limited soil disturbance in front of the borehole. However, there is one basic difficulty with that placement: the drill bit is rotating with the downhole motor, whereas the rest of the excavation equipment is stationary. A slipring or rotary coupling will have to be made for the wires leading to the cone. Such rotary connections are subject to high wear and are likely to cause problems, especially loss of voltage.

Referring to Figure K.2, it can be noted that the pore pressure is registered by a pore pressure transducer (P.P.T.). This transducer has an output in the millivolt range, with an excitation current of 5 volts. The Draper Laboratory found by experimentation that it was impossible to build a slipring for these small voltages (Martin, 1975). Therefore, an electronic package (EL) is necessary to convert the millivolt reading into a digital number. Powered by the battery, this digital reading can be transmitted through the wires and slipring to a surface readout unit.



a) CONE MOUNTED IN DRILL BIT MODULAR SPACE



b) MODULAR SPACE ADAPTION

FIGURE K.2
PIEZOMETER CONE CONFIGURATION

Figure K.2 presents diagrammatically how the piezometer cone extends from the bit. The modular space in the drill bit can be pressurized with air or oil, forcing the cone out like a piston in a cylinder. Both the cone end and the modular space opening contain piston rings to seal off the modular space (black squares on the drawing). A maximum pressure of 2000 psi (1.4 x 10^4 kN/m^2) in the modular space will give the cone a 3 ton (2.7 x 10^3 kg) penetration force, which should be more than sufficient in any soil. Instead of employing a fairly low vacuum force to withdraw the cone, it can simply be "drilled into" the modular space again. The air or oil supply for the cone extension will have to be taken through a "swivel," located at the rear of the drilling motor. This would be a miniature version of the rotary connection employed for the drilling mud on vertical working drill rigs. To eliminate the difficulties in such a swivel, the cone might be connected rigidly to the drill bit. However, the cone would be more vulnerable, obtain no penetration resistance measurements, and always be encompassed by a circumferential zone of sheared soil.

The apparently most suitable placement of the slipring and swivel would be at the uphole end of the motor. A centered hole would then have to be passed all the way through the motor and connections down to the drill bit. The Dyna-Drill motor does not rotate concentrically, and has a knuckle-joint connection with the bit (See Figure D.2). The electric motor requires a gear box. Both motors cannot accommodate a centered hole down to the drill bit. The Nichols motor is thus the only motor that allows use of the modular space on the drill bit.

The pressure in the modular space and thus the cone penetration resistance can be monitored by a pressure transducer mounted on or near the swivel. If a controlled penetration rate of the cone is desired, hydraulic oil rather than air must be used for the extension. Monitoring a metal piece or mercury drop in the oil line would be better suited for penetration measurement than a volume measuring valve.

Field testing of the piezometer cone (Wissa et al, 1974) revealed that excess pore pressure generated by the cone dissipated within 5-6 minutes in silty sand, but took 2-3 hours to dissipate in clayey silt. It would probably not be feasible to halt the excavation for such a long time. However, all three parameters measured by the piezometer (permeability, density and pore pressure) are deduced from the excess pore pressure level and its dissipation with time to a final value. If only 2-3 minutes can be spared for cone measurements, the penetration resistance and spatial pore pressure variations might be the only valuable result.

K.4 FOLLOWER PACKAGES

Appendix H discussed the various aspects of the stability of horizontal boreholes. It was found that in most soils (open gravels and very soft clays excepted) the stability could be achieved with

common drilling muds and properly designed fluid flow system. If long term stability of soft soils is a problem, the drilling mud in the borehole can be replaced by heavier mud after completion of the hole and retraction of the excavation equipment. Leaving a wire in the borehole would thn allow "follower packages" (borehole logging tools, etc.) to be pulled through the hole.

The follower packages considered in the subsequent section are those which can yield information about subsurface soil and water parameters despite soil disturbance around the borehole.

NUCLEAR LOGGING. Various nuclear logs (See Appendix J) can be employed to obtain soil density and water content provided the soil mineralogy is known. The very limited usage of these tools in vertical holes in soft ground suggests they will probably not be employed in horizontal holes either.

HYDRAULIC FRACTURING. This method involves sealing off and pressurizing a section of borehole. Monitoring the flow rate with time into this section may yield an estimate of the initial horizontal stress in the ground. This stress is in soft ground, however, not a widely varying tunnel design parameter and may not be as valuable to measure as geohydrological parameters.

SIDE WALL SAMPLING. Both Schlumberger (1974) and Hunt (1975) produce side wall samplers. The retrieved samples will of course be disturbed, but are well suited for soil classification, index tests and remolded strength tests. The Schlumberger sampler can retrieve a maximum of 72 samples, 1 3/4 in. (4.4 cm) long and 1 in. (2.5 cm) in diameter.

ELECTROMAGNETIC NUCLEAR RESPONSE. Application of an electromagnetic field to the strata around a borehole effects the unbound ions in the soil. The ions rotate to new positions, and when the field is removed, the ions precess back to their alignments with the earth's magnetic field at a constant precession rate for each particular element. This generates a secondary electromagnetic field, proportional in strength to the total number of ions. Since most mobile ions are hydrogen, the secondary field strength represents the total amount of free and mobile water in the soil. Empirical data suggest that the mobile ion content is directly related to the soil permeability. As the permeability is a very important soft ground tunneling parameter, this method seems worth future development. Further field testing and correlations are necessary before permeability can be measured quantitatively. Birdwell (1974) produces a 15 ft (4.6 cm) long induction log for holes over 5 in. (12.7 cm) in diameter that measures a hollow cylindrical zone 10 in. (25 cm) to 250 in. (6.3 m) from the tool axis. Thus the major part of the measurement will be outside the disturbed soil zone.

CALIPER. The four-arm caliper produced by Schlumberger (1974) appears ideal to measure time-deformation of horizontal boreholes larger than 6 in. (15.2 cm) in diameter. The caliper needs

modifications in the form of supports to ensure approximate centering in horizontal boreholes. The concept of measuring stand-up time will then be as follows: Two to four calipers are placed in the borehole in selected strata, and borehole mud diluted with injected water. The deformations occuring both with the reduction of the internal pressure in the borehole and by constant pressure will yield information which might be correlated with the stand-up time behavior of a subsequent tunnel. Development and field testing of this technique is highly recommended.

The follower packages that seem valuable for subsurface exploration are thus seismic logging with air guns (See Appendix J), side wall sampling, electromagnetic nuclear response and caliper measurements. Due to the damage to the borehole wall that might occur with these different exploration methods, thought should be given to the measurement sequence.

APPENDIX L

TUNNELING COST INCREASES RESULTING FROM UNANTICIPATED SUBSURFACE CONDITIONS

L.1 INTRODUCTION

Following a preliminary evaluation of the available data relating tunneling cost overruns to unanticipated geologic conditions, a procedure was established to recast the data for the value analysis of the tunnel exploration with horizontal penetration. This procedure is illustrated in Figure L.1; discussion of this procedure follows.

L.2 DOLLAR NORMALIZATION

In the first step the cost data was normalized with respect to time and location. The reference was chosen as the value of a dollar in Chicago at the beginning of 1974.

The normalizing factors were calculated from the "City Cost Indices in Building Construction Cost Data"(Means, 1975). There are two components of the correction factor: (1) a historical index (year-to-year) and (2) a geographical index (city-to-city). The geographical index has three components: (a) material, (b) labor, and (c) total. The numerical value of these three components was obtained by averaging the indices for the following items: forms, reinforcing, CIP concrete, carpentry, moisture protection, mechanical and electrical. The historical index was transferred back one year since 1974 is the reference year.

Data from a sensitivity analysis of a tunneling cost model developed for the Transportation Systems Center of DOT (Bechtel, A. D. Little, 1974) had already been escalated to 1974 figures. Therefore, normalizing factors were not needed. Even though this escalation did not include a reference to a particular city, the final estimates derived in this report should not be seriously affected. At most, the dollar figures derived from the sensitivity analysis may be 10% higher than other dollar figures due to this partial normalization.

L.3 DATA PRESENTATION

In the next step the cause-and-effect relationships for tunneling cost overruns were determined. Three physical variables were labeled as the primary causes--high groundwater flows, large and frequent boulders, and many utilities. Direct effects of misestimates of these variables result largely in increases in excavation cost. However, the effect also extends indirectly to all other work events. This

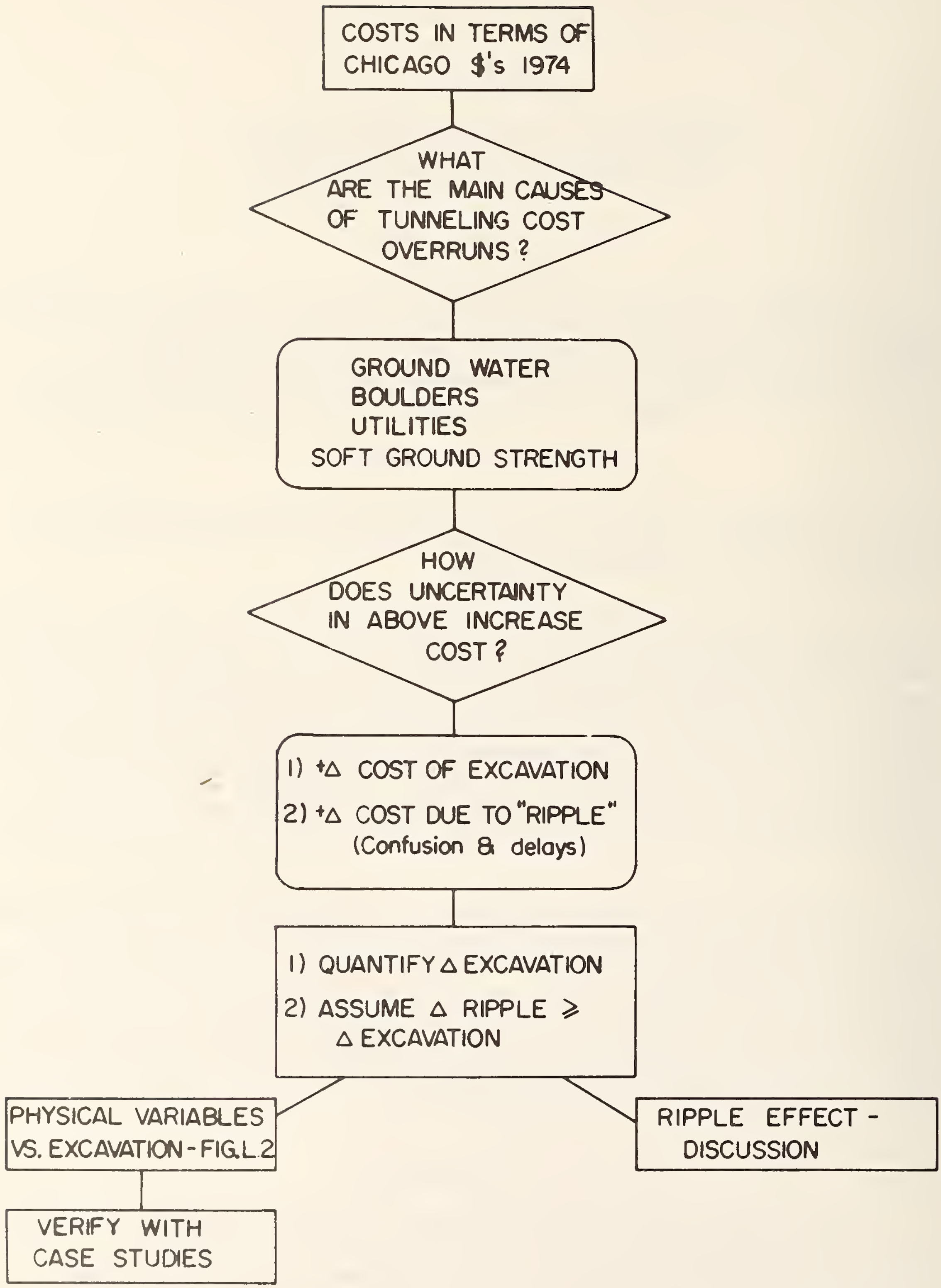


FIGURE L.1 METHODOLOGY : VALUE OF SUBSURFACE INFORMATION

indirect ripple effect is important and is discussed in Chapter 4.

The approximate relation between excavation cost and the level of adversity of the chosen physical variables is presented in Figure L.2. The relationships shown were developed from the data in Tables L.1 and L.2. These tables present basic costs for various work events and cost variations resulting from changes in physical and institutional factors (controls). In this section, only the cost of the basic work events and the effect which groundwater, boulders, and utilities have on this cost will be considered.

Tables L.1 and L.2 show that excavation and liner-grouting constitute about 83% of the basic cost of tunneling. The liner-grouting work event can be broken down further, as shown in Table L.3. Tunnel liners themselves constitute 65% to 70% of the liner-grouting work event, while the remainder is minor materials and labor. A change in the level of adversity of any physical variable will affect the labor cost the most. As the state-of-the-art in liner designs exists today, there should be little more than inflationary increases in liner costs. Consequently, changes in the level of adversity of the physical variables will be assumed to affect only excavation costs.

Cost of the basic work events shown in Tables L.1 and L.2 were calculated for a medium level of physical variable adversity and a low, or optimal, level of institutional adversity. Under ideal conditions, both physical adversity and institutional adversity would be at their optimal (low) level, in which case the tunnel(s) could be constructed for a minimum cost. The cost under these conditions is the Basic Excavation Cost (BEC) in Figure L.2.

In order to determine the BEC, the change in excavation cost resulting from a change in physical adversity from a low to medium level must be subtracted from the excavation cost shown in Column 2 of Table L.1. Since changes in physical adversity have been assumed to affect only the cost of excavation, the increase in excavation cost when the level of physical adversity changes from low to medium is given in Column 4a of Tables L.1 and L.2. The physical variables are included under the headings of utility density and ground conditions. The effect of utilities and boulders will be obtained from Table L.1 (free-air) so that the effect of each physical variable can be estimated independently of the others. Table L.1 served as a base since cost increases associated with compressed air tunneling (Table L.2) were assumed to result from high ground water adversity.

To remove the effect of utilities, \$96/ft (\$315/m), Column 4a, Table L.1 , is subtracted from the excavation cost. In order to remove the effect of boulders and groundwater, the components of "ground conditions" must be estimated. Because of their overwhelming importance in construction rates, boulders and groundwater effects will be assumed

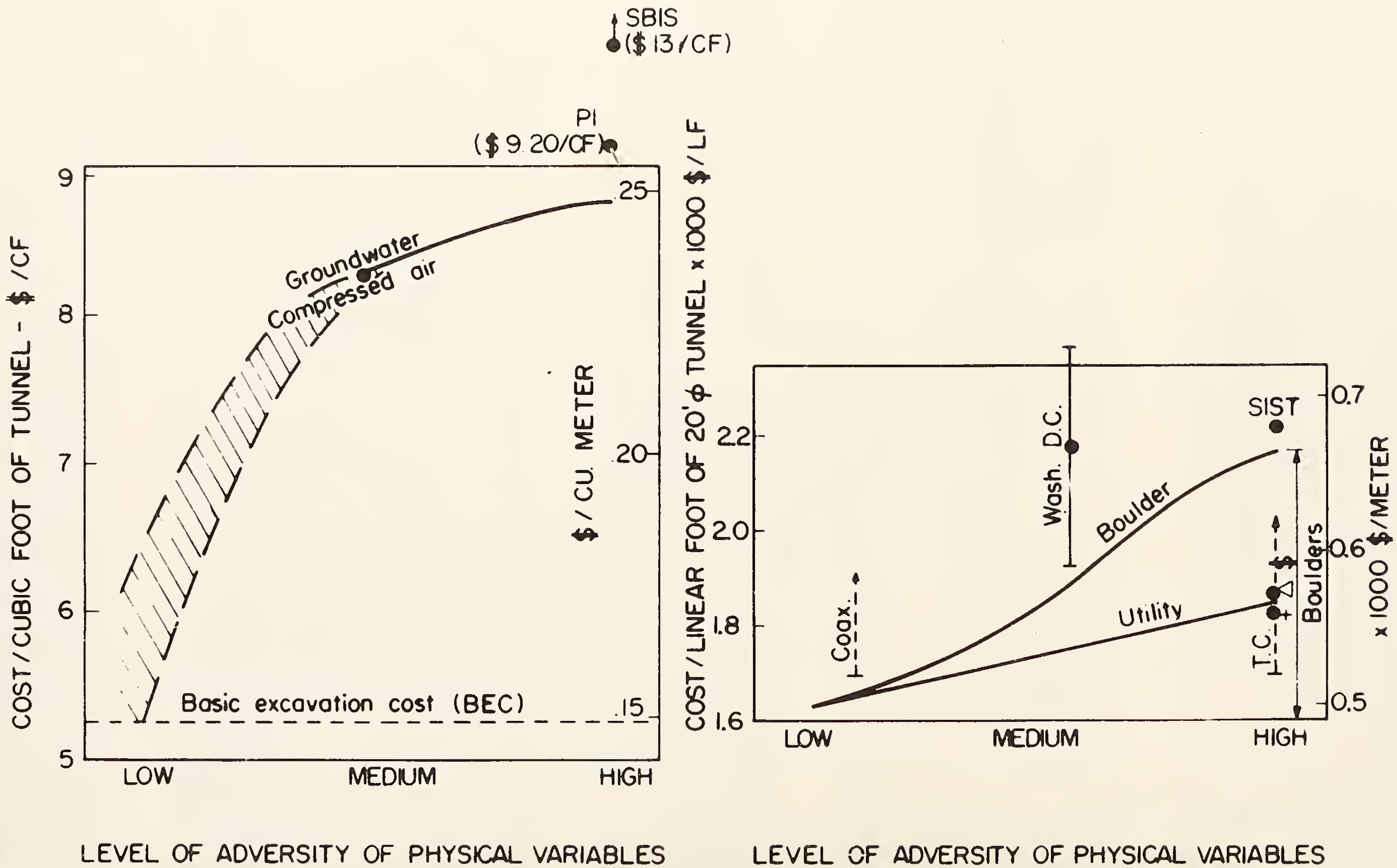


FIGURE L.2 EXCAVATION COST INCREASE DUE TO ADVERSE PHYSICAL VARIABLES

TABLE L.I
SENSITIVITY ANALYSIS FOR FREE-AIR-DRIVEN TUNNEL MODEL
(After Bechtel, A. D. Little, 1974)

Sensitivity Parameters	Program Input Values at Medium Physical & Moderate Institutional Control ($/LF)	Change in level of adversity	Resulting Change in Total Project Cost ($/LF) †		Resulting Percentages Change in Total Project Cost (%)	
Work Events						
Mobilization	167	±10%	± 16.7		±0.36	
Workshaft	272		± 27.2		±0.59	
Underpinning	100		± 10.0		±0.22	
Excavation	2,000		±200.0		±4.36	
Muck Disposal	80		± 8.0		±0.17	
Liner, Grouting	1,800		±180.0		±3.92	
Concrete	170		± 17.0		±0.37	
	4,589					
Physical Controls			4a	4b		
Utility Density		Low High	- 96.0	+ 96.0	- 2.09	+ 2.09
Traffic Conditions			- 4.0	+ 4.0	- 0.09	+ 0.09
Existing Structures			-204.7	+313.4	- 4.46	+ 6.83
Ground Conditions			-265.2	+335.6	- 5.78	+ 7.31
Fill Demand			- 40.0	+ 40.0	- 0.87	+ 0.87
					-13.29	+17.19
Institutional Controls						
Optimal Project Schedule		Med High	+ 53.33	+133.33	+ 1.16	+ 2.91
System-Wide Labor Agreement			+ 53.33	+ 80.00	+ 1.16	+ 1.74
Owner-Acquired Work Areas			+ 53.33	+106.67	+ 1.16	+ 2.32
Owner-Acquired Right-of-Way			+ 53.33	+106.67	+ 1.16	+ 2.32
Owner-Acquired Entry Permit			+ 26.67	+ 93.33	+ 0.58	+ 2.03
Owner-Acquired Building Permit			+ 27.84	+ 29.00	+ 0.61	+ 0.64
Owner-Supplied Material			+218.53	+613.68	+ 4.76	+13.37
Owner-Purchased Insurance			+111.05	+129.41	+ 2.42	+ 2.82
Owner-Enforced Environmental Regulations			0	0	—	—
Safety			+ 24.67	+447.85	+ 0.54	+ 9.76
Labor Productivity			+ 85.33	+426.67	+ 1.86	+ 9.30
Advance Payment			+ 5.00	+ 7.50	+ 0.11	+ 0.16
Efficient Cash Flow			+ 11.47	+ 68.84	+ 0.25	+ 1.50
					+15.77	+48.87

† Based on a 20 ft (6.1m) diameter tunnel

(1 ft. = 0.305 m)

TABLE L.2
SENSITIVITY ANALYSIS FOR COMPRESSED-AIR-DRIVEN TUNNEL MODEL
(After Bechtel, A. D. Little, 1974)

Sensitivity Parameters	Program Input Values at Medium Physical & Moderate Institutional Control ($/LF)	Change in Value of Input	Resulting Change in Total Project Cost ($/LF)		Resulting Percentage Change in Total Project Cost (%)	
Work Events						
Mobilization	233	±10%	± 23.3		±0.40	
Workshaft	326		± 32.6		±0.56	
Underpinning	100		± 10.0		±0.17	
Excavation	2,950		±295.0		±5.08	
Muck Disposal	80		± 8.0		±0.14	
Liner, Grouting	1,950		±195.0		±3.3	
Concrete	170		± 17.0		±0.29	
	5,809					
Physical Controls			4a	4b		
Utility Density		Low High	-141.6	+141.6	- 2.44	+ 2.44
Traffic Conditions			- 4.0	+ 4.0	- 0.07	+ 0.07
Existing Structures			-253.7	+365.7	- 4.37	+ 6.30
Ground Conditions			-372.4	+450.8	- 6.41	+ 7.76
Fill Demand			- 40.0	+ 40.0	- 0.69	+ 0.69
					-13.98	+17.26
Institutional Controls						
Optimal Project Schedule		Med High	+ 66.67	+166.67	+ 1.15	+ 2.87
System-Wide Labor Agreement			+ 66.67	+100.00	+ 1.15	+ 1.72
Owner-Acquired Work Areas			+ 66.67	+166.67	+ 1.15	+ 2.87
Owner-Acquired Right-of-Way			+ 66.67	+133.34	+ 1.15	+ 2.30
Owner-Acquired Entry Permit			+ 33.33	+116.67	+ 0.51	+ 2.01
Owner-Acquired Building Permit			+ 34.50	+ 34.50	+ 0.59	+ 0.59
Owner-Supplied Material			+229.90	+688.71	+ 3.96	+11.86
Owner-Purchased Insurance			+135.35	+160.33	+ 2.33	+ 2.76
Owner-Enforced Environmental Regulations			+ 45.33	+ 56.67	+ 0.78	+ 0.98
Safety			+ 44.74	+668.51	+ 0.77	+11.51
Labor Productivity			+125.33	+626.67	+ 2.16	+10.79
Advance Payment			+ 8.00	+ 12.00	+ 0.14	+ 0.21
Efficient Cash Flow			+ 14.52	+ 87.14	+ 0.25	+ 1.50
					+16.15	+51.97

(1 ft. = 0.305 m)

to constitute 95% of "ground conditions." With these data, the BEC can be determined:

$$\text{Basic Excavation Cost} = \begin{array}{l}\text{Cost with medium}\\ \text{physical adversity}\end{array} - \begin{array}{l}\text{effect of utilities and}\\ \text{ground conditions}\end{array}$$

$$= \$2000/\text{LF} - \$96/\text{LF} - 0.95\ (\$265.2/\text{LF})$$

$$= \$1652/\text{LF}$$

It should be noted that the BEC shown above is not the minimum excavation cost since other physical variables are still present at a medium level.

Figure L.2 shows the trends that the cost of excavation follows as the level of physical adversity changes. The BEC has been expressed in terms of $/CF ($\$/m^3$) and $/LF ($/m) depending on which is appropriate for the physical variable being considered.

The relation between excavation cost and the number of utilities of a given kind is a linear function. The slope of the line will depend on the type of utilities encountered. The value shown in Table L.1, a $96/LF ($315/m) increase from low to medium and medium to high, could be considered an average value for the types of utilities encountered in tunnel construction. See Section L.4 for a discussion of extreme cases.

To estimate the effects of groundwater separately from boulders, the cost increases due to each had to be separated. The two physical variables were listed under the same heading, "Ground Conditions" in Tables L.1 and L.2. Therefore it was necessary to know what percentage was attributed to boulders above as the level of adversity increased.

Dewatering costs were assumed low up to medium levels of groundwater adversity and groundwater in the low to medium adversity range was assumed to have only a small effect on excavation cost increase. It was assumed to cause 20% of the increased cost (Table L.1, Column 4a) from low to medium levels, boulders 75% and miscellaneous 5% of the increase. It was then assumed that above a medium level, further increases in groundwater effects will require the use of compressed air to control construction. (Although there is no sharp line dividing the situations where compressed air is used and not used, it was necessary to do so for utilization of the data in the tables.) This groundwater assumption requires that for a free-air tunnel (Table L.1), when ground conditions change from a medium to high level of adversity, "Ground Conditions" would then consist of: boulders--95%, miscellaneous--5%, since increased effects of groundwater would result in a compressed-air tunnel.

The above assumptions and the previous percentages then permit a calculation of the increase in cost for the effects of boulders as shown in Figure L.2. The resulting relationships will be checked with independent data for verification. See Section L.4 for the cases which serve as an independent check of these derived relationships.

TABLE L.3: COST SUMMARY FOR GENERALIZED TUNNEL MODEL

(After Bechtel, A. D. Little, 1974)

Work Event	Unit	3200 ft Free-Air Unit Costs* $/System Ft	3200 ft Free-Air Amount* $	3000 ft Compressed-Air Unit Costs* $/System Ft	3000 ft Compressed-Air Amount $
Shaft Construction	L.S.		$ 815,000		$ 978,000
Mobilization	L.S.		500,000		700,000
Underpinning	LF	100	300,000	100	300,000
Tunnel Driving Costs					
Liner Erection and Caulking	LF	300		400	
Grouting	LF	240	5,400,000	290	5,850,000
Tunnel Liners	LF	1260		1260	
Excavation	LF	2000	6,000,000	2950	8,850,000
Disposal	LF	80	240,000	80	240,000
Concrete Construction	LF	170	510,000	170	510,000
TOTAL		4588	$13,765,000		$17,428,000
Labor		37%		43%	
Equipment and Materials		63%		57%	

* All costs reflect a January 1, 1974, bid date.

(1 ft. = 0.305 m)

Similar estimates for the effects of groundwater involved a comparison of the cost of work events as shown in Tables L.1 and L.2. The difference in cost of basic work events between a free-air tunnel and a compressed-air tunnel are assumed to be solely a result of poor groundwater conditions. Therefore, there is a basic excavation cost increase of \$950/LF (\$3114/m) at a medium level of physical adversity. The determination of cost increases at a higher level of physical adversity required a further assumption. Boulder and groundwater effects were assumed to account for 100% of the cost change shown in Table L.2, Column 4. Then the effect of boulders (obtained previously) can be subtracted to yield the effect of groundwater alone for changes in adversity within a compressed-air tunnel. The results are shown in Table L.4.

TABLE L.4

Variable	Combined Net Change \$/LF	% Effect Due to Variable	Net Change (over BEC) \$/LF
Boulders	low to medium 265[1]	75	200
	medium to high 336[1]	95	319
		Boulder Effect \$/LF	
Groundwater	low to medium 372[2]	200	172
	medium to high 451[2]	319	132

[1] From Table L.1

[2] From Table L.2

(1 ft. = 0.305 m)

To obtain the cost of excavation at a certain level of physical adversity, the net change shown in Table L.3 for the appropriate variable and adversity is added to the BEC. The BEC for the utility and boulder categories is \$1652/LF (\$5416/m) as determined previously. However, because of the increase in excavation cost due to compressed air, the reference cost for groundwater has been increased. Table L.3 indicates

that when physical variable adversity is at a medium level, the excavation cost is \$2950/LF (\$3115/m). The comparable reference cost for groundwater at medium adversity is then \$2950/LF (\$3115/m) minus the change in excavation cost due to all variables increasing in adversity from a low to medium level. This change is given in Table L.2, Column 4a, for utility density and ground conditions and in Table L.5 for boulder discount.

$$\begin{aligned}
\text{Reference Cost (at medium)} &= \text{Excavation Cost Compressed-Air} - \text{due to (utility + ground condition)} \\
&\quad + \text{due to water low to medium} \\
&= \$2950/\text{LF} - (142 + 372)\$/\text{LF} + 172 \\
&= \$2608/\text{LF}
\end{aligned}$$

With the reference costs and the net changes from Table L.4, the coordinates shown in Table L.5 can be calculated and plotted as in Figure L.2. The resultant costs at each level of adversity reflect the influence of only the one variable considered.

TABLE L.5: RESULTANT EXCAVATION COST DUE TO CHANGE IN INPUT LEVEL OF PHYSICAL VARIABLES (\$/LF TUNNEL)

Variable	Adversity Low	Adversity Medium	Adversity High
Utility	1652	1748	1844
Boulder	1652	1852	2170
Groundwater	1652	2608	2741

(1 ft. = 0.305 m)

L.4 CASE STUDIES--VALIDATION OF FIGURE L.2

The appropriateness of Figure L.2 can be determined by examining a few additional case studies. Table L.6 includes a description of useful case studies from "Systems Analysis Modeling and Optimization of Rapid Transit Tunneling" (Schmidt, et al, 1974). Case studies involving utility obstruction and grouting were also obtained and will be described later. Data from all of the case studies were reduced to a compatible form and plotted on Figure L.2.

TABLE L.6: CASE STUDIES
(from Schmidt, 1974)

Project	Tunnel Description	Soil Description/ Ground Condition	Problem Encountered or Unexpected Condition	Associated Cost Increase	Normalized Cost Increase
Staten Island Sewer Tunnel N.Y. (1973-1974) (SSI)	7000 ft 9 ft diam. Steel liner	glacial till areas of heavy boulders variable ground-water severity	Boulder size and frequency = TBM Mucker inadequate.	$600/LF	$550/LF
			Specs required compressed-air plant for uncertain groundwater conditions; unneeded.	$500,000	$510,000
			Collapse of unpredicted 16 in. live sewer over heading.	$5000	$4625
South Branch Interceptor Sewer New York, N. Y. (1962-1964) (SBI)	18,000 ft 12 ft diam. At Bid: 8000 ft tunnel 10,000 ft C and C	On East Side, Lower Manhatten	Numerous man-made obstructions severely hindered dewatering 8000 ft constructed under compressed air.	$17 M (1974 $) $2125/LF	$1960/LF
Sewer Tunnel (1957-1959) (?)	12 ft diam. At Bid: 5000 ft C. Air 1000 ft C and C	Groundwater	10-week difference in time to construct two identical 80 ft shafts; one predicted perched water table, other did not.	Difference ≈$500,000	≈$500,000
		Groundwater	Cut and Cover section constructed under compressed-air for water control; running ground from old creek bed caused building settlement.	$1 M (1974$)	≈$1000/LF (Minimum)

(1 ft. = 0.305 m)

STATEN ISLAND SEWER TUNNEL (SIST)

The contractor encountered more frequent and larger sized boulders than had been indicated by the preliminary investigation. The mucker on the tunnel boring machine proved inadequate and required had breaking of the boulders. The rate of advance decreased drastically with a resultant increase in excavation cost. In normalized dollars, the increase was $550/Lf ($1803/m) from the originally predicted low frequency and size to the encountered high boulder frequency. Figure L.2 yields a $518/Lf ($1698/m) increase, which is a good correlation with this independent case.

WASHINGTON METRO (WM)

The data on this one case is hearsay due to current litigation but is indicative of the magnitude of the problem (Hansmire, 1975). A shield-driven tunnel encountered rock along the invert and boulders at the crown; the former is a result of a plotting error. The contractor hand-minded an 800 ft (244 m) section at a cost of about $1 M (1972-73). Half of this cost can be attributed to confusion of responsibility and indecision. A cost increase of $1475/Lf (1974) ($4836/m) thus resulted.

The excavation cost increase is subject to a great deal of uncertainty, and is therefore plotted as a range in Figure L.2. The upper bound represents an excavation cost increase of one-half the total.

CUT AND COVER CONVERSION TO COMPRESSED AIR

The next two cases involved a conversion from cut-and-cover to compressed-air tunneling in order to control water inflow. Figure L.2 relates the effect of physical adversity to excavation cost only for free-air and compressed-air tunnels. The data from these cut-and-cover case studies must be corrected to account for the difference in excavation method. To convert from cut-and-cover to tunnel cost, reference was made to the basic cost data shown in Column 1 of Tables L.1, L.2, and L.7 for free-air, compressed-air, and cut-and-cover respectively. Since a change in construction methods involves changes in the cost of all work events, the comparable total cost increase in these case studies was assumed to result from only an increase in excavation cost. Therefore the change in excavation cost will be proportioned as shown in Table L.8.

From Table L.8 it can be seen that the increase in excavation cost is 89% of the total cost increase for converting cut-and-cover construction to a compressed-air tunnel. But of this amount, only half, or 44.5%, can be attributed to an excavation cost increase above the free-air excavation cost. This latter number will be used to refer the case studies to Figure L.2.

TABLE L.7
SENSITIVITY ANALYSIS FOR CUT-AND-COVER LINE MODEL
(After Bechtel, A.D. Little, 1974)

Sensitivity Parameters	Program Input Values at Medium Physical and Moderate Institutional Control ($/LF)	Change In Value of Input	Resulting Change in Total Project Cost ($/LF)		Resulting Percentage Change in Total Project Cost (%)	
Work Events						
Utilities	804	±10%	- 80.4	+ 80.4	- 2.19	+ 2.19
Deck and Traffic Control	289		- 28.9	+ 28.9	- 0.79	+ 0.79
Underpinning	100		- 10.0	+ 10.0	- 0.27	+ 0.27
Excavation	1,050		-105.0	+105.0	- 2.86	+ 2.86
Muck Disposal	104		- 10.4	+ 10.4	- 0.28	+ 0.28
Concrete	952		- 95.2	+ 95.2	- 2.59	+ 2.59
Backfilling	67		- 16.7	+ 16.7	- 0.45	+ 0.45
Restoration	108		- 10.8	+ 10.8	- 0.29	+ 0.29
Miscellaneous	102		- 10.2	+ 10.2	- 0.27	+ 0.27
	3,676					
Physical Controls						
Utility Density		Low High	-478	+1,335	-12.73	+36.32
Traffic Conditions			-394	+ 517	-10.72	+14.06
Existing Structures			-105	+ 580	- 2.86	+15.78
Ground Conditions			- 65	+ 333	- 1.77	+ 9.06
Fill Demand			- 52	+ 52	- 1.41	+ 1.41
Architectural Requirements			0	0	0	0
Weather			-170	+ 172	- 4.62	+ 4.68
					-34.11	+81.31
Institutional Controls						
Optimal Project Schedule		Med High	+ 17.4	+ 34.8	+ 0.47	+ 0.95
System-Wide Labor Agreement			+ 17.4	+ 26.1	+ 0.47	+ 0.71
Owner-Acquired Work Areas			+ 17.4	+ 17.4	+ 0.47	+ 0.47
Owner-Acquired Right-of-Way			+ 17.4	+104.4	+ 0.47	+ 2.84
Owner-Acquired Entry Permit			+ 8.7	+ 30.5	+ 0.24	+ 0.83
Owner-Acquired Building Permit			+ 8.7	+ 8.7	+ 0.24	+ 0.24
Owner-Supplied Material			0	0	0	0
Owner-Purchased Insurance			+ 45.6	+ 54.0	+ 1.24	+ 1.47
Owner-Enforced Environmental Regulations			+ 43.4	+ 65.1	+ 1.18	+ 1.77
Safety			+ 75.9	+330.0	+ 2.06	+ 8.98
Labor Productivity			+114.7	+573.5	+ 3.12	+15.60
Advance Payment			+ 4.7	+ 7.0	+ 0.13	+ 0.19
Efficient Cash Flow			+ 9.2	+ 55.1	+ 0.25	+ 1.50
					+10.34	+35.55

(1 ft. = 0.305 m)

South Branch Interceptor Sewer (SBIS)

South Branch Interceptor Sewer was bid with 10,000 ft (3050 m) of cut-and-cover construction. Of this amount, 8000 ft (2440 m) was finally constructed as a compressed-air tunnel because numerous unpredicted obstacles severely hindered the dewatering operations. The cost increase was approximately $15.7 million, or $1960 per linear foot ($6426/m) of compressed-air tunnel. Forty-four and one half percent of this amount of $872/Lf ($2859/m) is the equivalent cost increase over the cost of a free-air tunnel (BEC).

1957-1958 Sewer Tunnel (? on Figure L.2)

Another case involved a similar sewer tunnel at an unknown location (?) . Similar to the previous case, a planned cut-and-cover section (1000 ft/305 m) was constructed under compressed air because of running ground resulting from dewatering problems. The total cost increase was approximately $1000/Lf ($3278/m) or an increased excavation cost of $445/Lf ($1459/m) above the free-air cost.

The level of adversity in the two previous cases was subjectively determined. Since the construction method was changed, the data were plotted at a high level of adversity.

UTILITY LINES

Data concerning the cost of severing various types of utilities was supplied by Titan Contractors (Sacramento, CA.). The following are average costs

telephone	$720
electrical	$465
gas	$125

With these costs the utility density required to cause the increased costs shown in Figure L.2 can be calculated. A high utility density is equivqlent to one (1) telephone cable approximately every 4 ft (1.2 m) at a high level of adversity.

These average costs are low since smaller or less important utilities are encountered most often. However, if one important utility is encountered, the cost can be astronomical. For example, severance of a coaxial cable for prime time TV can cost as much as $100,000 per minute. Severance of a main gas line can cost more than $10,000.

GROUTING: SOUTHSIDE INTERCEPTOR (SSI)

A 10 ft (3.1 m) diameter sewer tunnel in Newark, N.J., encountered unstable conditions while being driven under a hydraulically-filled enbankment of the Lehigh Valley Railroad (Herndon, 1975). Running

ground and vibrations from the train makeup yard made excavation difficult. The 350 ft (107 m) section was advanced to within 120 ft of completion using wellpoints, grout, or shield to overcome the water and loading problems. Further chemical grouting was necessary to complete the tunnel.

The case description did not allow a detailed assessment of the exact role and cost of grouting. Therefore assumptions had to be made. The cost of grouting was assumed to represent the increased excavation cost. At a cost of \$2000 per day for a grout crew (Parker, 1970) and an estimated completion time (for grouting) for the final section of 15 days, an excavation cost increase of \$3.40/Lf (\$121/m^3) results. This figure is most likely lower than the actual increase.

TABLE L.8

Source	Table L.7	Table L.1	Table L.2
	Cut & Cover	Free Air	Compressed Air
Total Cost	3676	4589	5089
Excavation Cost	1050	2000	2950
	\$950/Lf		\$950/Lf
	50%		50%
		\$1900/Lf	
		\$2133/Lf	

(1 ft. = 0.305 m)

APPENDIX M

COSTS AND CONSIDERATIONS OF SURFACE EXPLORATION

M.1 INTRODUCTION

This appendix deals with two principal methodologies: vertical boring and near surface geophysical exploration. The following topics are discussed in detail: Vertical boring and testing costs (M.2) and near surface geophysical exploration: costs and considerations (M.3). The vertical boring section is divided into (1) Costs on dry land, (2) Costs over water, (3) Urban boring costs, (4) Cone penetrometer costs, and (5) Accuracy and considerations of vertical boring. The geophysical exploration section is divided into (1) Surface geophysical exploration costs, (2) Refraction survey considerations, (3) Reflection survey considerations, (4) Electromagnetic survey considerations, and (5) Vertical borehole geophysics: costs and considerations.

M.2 VERTICAL BORING AND TESTING COSTS AND CONSIDERATIONS

COSTS ON DRY LAND

Boring and testing costs were estimated separately and then totaled by region. When more than one data source was available, costs were averaged to simplify cost estimates since unit prices often varied by more than ±50% (from the average). All costs are in terms of 1974 dollars.

Tables M.1 and M.2 summarize the boring and testing data from the Washington Metropolitan Area Rapid Transit subsurface investigation. Sample calculations follow to illustrate computation of testing costs utilizing items from Tables M.1 and M.2 and their associated costs as obtained from various sources (Golder Gass Associates, 1975; Haley and Aldrich & Associates, Inc., 1975; and Woodward-Moorhouse & Associates, Inc., 1975).

In order to calculate the cost of a model exploration program, assumptions were made and used along with the data from Tables M.1 and M.2. The first assumption was the depth at which bedrock is encountered. This parameter is a function of the bedrock topography in the geographic region being considered, and it must take into account the probability of encountering that condition. For example, in the Southern U. S. (Gulf of Mexico region), at depths of 50 ft, 100 ft, and possibly 500 ft (15.2 m, 30.5 m, and 152 m), bedrock is rarely encountered, while in the Northeastern U. S. bedrock can be encountered at all of these depths. The following drilling conditions are thus assumed:

TABLE M.1: CHARACTERISTICS OF BORING DATA FROM WMATA (CONNECTICUT AVE.)

ITEM	QUANTITY
No. of borings [1] Total Length of Routes	323 101,380 ft
	Average Boring Spacing - 314 ft
Length of Wash Borings [2]	2½"ϕ 5259.7 ft 3½"ϕ 6970.8 ft Total 12230.5 ft
	Average Depth of Wash Boring - 38 ft
Length of Rock Core	5537.4 ft
	Average Depth of Rock Core - 17 ft
	Average Depth of Boring - 55 ft
Number of Undisturbed Samples [3]	2"ϕ 109 3"ϕ 271 Total 380
Number of Observation Wells Length of Standpipe for Observation Wells	79 4410.7 ft
	Average Depth of Observation Well - 56 ft Average Number of Wells per Foot of Tunnel - 0.00078

1. includes 21 supplemental borings to sample bedrock and clay stratum
2. inlcudes Split Spoon samples, generally on 5 ft (1.5 m) centers
3. includes undisturbed samples from 7 supplementary borings

(1 ft. = 0.305 m; 1 in. = 2.54 cm)

TABLE M.2: CHARACTERISTICS OF LABORATORY TESTING DATA FROM WMATA (CONNECTICUT AVENUE)

Test	Total Number of Tests	Average Number of Tests per Boring*
Water Content	1651	5.1
Atterberg Limits	493	1.5
Grain Size Analysis	247	0.77
Permeability**	10	0.03
Compaction	6	0.02
Unconfined Compression	166	0.51
Triaxial Test		
Q (UU)	232	0.72
Q_c (CU)	14	0.04
S (CD or $\overline{CU}$)	5	0.02
$\sigma - \varepsilon$ curves	89	0.28
Direct Shear (undrained @ F.M.)	81	0.27
Consolidation	89	0.28
Ph	110	0.34
Electrical Resistivity	110	0.34
Chemical Analysis	93	0.29

* This is the average number of tests per boring for an average boring depth of 55 ft (16.8 m). Correction factors of 1.25 and 1.4 will be applied for depths of 100 ft and 500 ft (30.5 m and 152.5 m) respectively, to account for an increased number of tests. The correction factors are arbitrary, however. Soil outside of the "general tunnel area" need not be tested except possibly at change of strata.

** Lab permeability only; does not include field tests.

Boring Depth	Depth to Rock Northeast	South
50 ft (15.2 m)	40 ft (12.2 m)	No
100 ft (30.5 m)	85 ft (25.9 m)	rock
500 ft (152.5 m)	500 ft (152.3 m)	encountered

Further assumptions include a drilling inspector charge of $130/day and an average penetration rate per rig of 40 ft/day (12.2 m/day) in the Northeast and 100 ft/day (30.5 m/day) in the South.

Since the average depth of observation well, 56 ft (17.1 m), was only slightly greater than the average depth of boring, 55 ft (16.8 m), all wells will be assumed to have the same depth as the borings.

Tables M.3 and M.4 illustrate the manner in which the average drilling and testing costs per boring were determined in the Northeast. Tables M.5 and M.6 show how these boring costs were translated to costs per foot of tunnel for the Northeast. Table M.7 then compares the resultant exploration costs for various regions of the country computed in a similar manner.

COSTS OVER WATER

The previous costs did not consider the effect of drilling over water. If such a situation did occur, there would be additional costs involved. Three items may be included as additional costs (depending upon the contractor):

1) Additional cost per foot of boring
2) Additional mobilization and demobilization charge
3) Barge and tug rental, with two crews

One or more of these items may be combined and expressed as a single price increase. For example, one contractor may bid with increases in all of the above items, while another may bid with only a higher mobilization and demobilization charge, or a higher cost per foot.

Table M. 8 gives boring cost and exploration cost increases due to drilling over water. The assumptions behind this table are listed below.

<u>Northeast</u> (little information)

1) Additional cost per foot soil--$2/ft rock--$3/ft
2) Mobilization and demobilization--10% of additional costs
3) Barge ($45/day) plus tug and crew ($20/hr) @ 24 hr/day--$525/day (For a drilling rate of 40 ft/day (12.2 m/day), the barge cost is $13.10/ft of boring.)

EXAMPLE CALCULATIONS

COSTS OF BORING, SAMPLING, AND TESTING

NORTHEASTERN U. S.

Undisturbed sample: (2 in. ϕ Shelby tube and 3 in. ϕ piston sampler)

Average of 14 contractor bids for 2 in. ϕ samples $21[1]

Average of 18 contractor bids for 3 in. ϕ samples $41[1]

Weighted average

2 in.: $21 x 109 2 in. samples = $ 2,289

3 in.: $41 x 271 3 in. samples = 11,111

380 samples $13,400

$$\frac{\$13,400}{380} = \$35/\text{sample}$$

$$\frac{\text{No. undisturbed samples}}{\text{No. borings}} = \frac{380}{323} = 1.2 \text{ samples per boring for a 55 ft (16.8 m) average depth}^{2}$$

Test Item	Average Cost ($)	Boring Average Depth/ft	#/boring x correction factor [3]	($) Cost/ Boring
Undisturbed sample	35	50 (15.2 m)	1.2 x 1.0	42
Atterberg limits	20	50 (15.2 m)	1.5 x 1.0	30
Grain size analysis	17	50 (15.2 m)	0.77 x 1.0	13.10

1 Data from Haley and Aldrich, 1975.

2 Data from Tables M.1 and M.2, this report.

3 For various average boring depths, corrections can be applied to adjust the average number of samples taken per boring. See Table M.2, footnote 1.

TABLE M.3: BORING COSTS IN NORTHEASTERN U. S.

Item	Quantities for an Average Boring Spacing of: 50 ft (15.2 m)	100 ft (30.5 m)	150 ft (45.8 m)	Unit Price [1]	Total for an Average Boring Depth of: 50 ft (15.2 m)	100 ft (30.5 m)	150 ft (45.8 m)
Wash Boring	40	85	500	$9.40/ft	$376	$799	$4,700
Undisturbed Sample[2]	1.2	1.5	1.7	$35/sample	42	53	60
Rock Core	10	15	0	$15.60/ft	156	234	0
Inspector	50	100	500	$3.25/ft[3]	162	325	$1,625
				Subtotal	$736	$1,411	$6,385
Observation Well[4]	50	100	500	$5.15/ft	$257	$515	$2,575

1 Averages from contractor data supplied by Haley & Aldrich, Inc.

2 See sample calculations.

3 Assuming a cost of $130/day and a drilling rate of 40 ft/day (12.2 m/day).

4 Totaled separately because of different normalizing factors.

TABLE M.4: LAB TESTING COSTS FOR TUNNEL EXPLORATION IN NORTHEAST U. S.

TEST	No. Tests/Boring*	Unit Price**	Cost/Boring*
Water content	5.1	$2	$10.20
Atterberg Limits	1.5	21	31.50
Grain Size Analysis	0.77	16	12.30
Permeability	0.03	60	1.80
Compaction	0.02	70	1.40
Unconfined Compression	0.51	22	11.20
Triaxial Test			
Q (UU)	0.72	13.50	9.70
R (CU)	0.04	27	1.08
S (CD or $\overline{CU}$)	0.02	125	2.50
$\sigma - \varepsilon$	0.28	10	2.80
Direct Shear	0.25	20	5.00
Consolidation	0.28	120	33.60
Ph	0.34	8.50	2.90
Electrical Resistivity	0.34	≃75***	25.00
Chemical Analysis	0.29	≃50***	14.50

TOTAL LAB TESTING COST PER BORING = $165.98

* This is the number of tests and cost for a boring which averages 55 ft (16.8 m)--recall that these quantities are assumed to apply to a boring 50 ft (15.2 m) in depth.

** Averages--Golder Gass Associates, Inc., 1975; Haley and Aldrich, Inc., 1974; Woodward-Moorhouse & Associates, Inc., 1973.

*** " ≃ " indicates cost estimate when unit price was not given.

TABLE M.5: BORING COSTS PER LINEAR FOOT OF TUNNEL

Boring Depth ft (m)	Cost Per Boring ($)	Normalized Cost ($)* Boring Spacing (Normalizing Factor = 1/BS) 50 ft (.02)	150 ft (.0067)	300 ft (.0033)
50 (15.2 m)	736	14.70	4.90	2.45
100 (30.5 m)	1411	28.20	9.45	4.70
500 (152.2 m)	6385	127.60	42.50	21.20
Well Depth ft (m)	**Cost Per Well ($)**	**Normalized Total** ** **Normalizing Factor, N.F. = 0.00078 well/ft tunnel**		
50 (15.2 m)	258	.20		
100 (30.5 m)	515	.40		
500 (152.2 m)	2575	2.00		

* $/Boring x 1/BS x 1.15

** $/Well x NF

TABLE M.6: TOTAL BORING COST* VS SPACING & DEPTH

(Dollars Per Linear Foot Of Tunnel)

Boring Depth ft (m)	Boring Spacing 50 ft (15.2 m)	150 ft (45.8 m)	300 ft (91.5 m)
50 (15.2 m)	17.15	5.86	3.05
100 (30.5 m)	32.90	11.30	5.86
500 (152.5 m)	149.00	51.10	26.70

* Total Cost = 1.15 x Normalized Total (Boring + Well), where 15% is added for mobilization and demobilization.

TABLE M. 7 : REGIONAL EXPLORATION COSTS PER FOOT OF TUNNEL
(In Dollars Per Linear Foot)

	Boring Spacing → / Boring Depth ↓	NORTHEAST 50 ft/ 15.2 m	NORTHEAST 150 ft/ 45.8 m	NORTHEAST 300 ft/ 91.5 m	SOUTH 50 ft/ 15.2 m	SOUTH 150 ft/ 45.8 m	SOUTH 300 ft/ 91.5 m	WEST*** 50 ft/ 15.2 m	WEST*** 150 ft/ 45.8 m	WEST*** 300 ft/ 91.5 m
BORING*	50 ft/ 15.2 m	17.15	5.86	3.05	8.10	2.88	1.56			
	100 ft/ 30.5 m	32.90	11.30	5.86	17.20	6.04	3.25	———	———	———
	500 ft/ 152.5 m	149.00	51.10	26.70	110.00	39.95	22.20			
TESTING*	50 ft/ 15.2 m	3.32	1.11	.55	3.32	1.11	.55	4.50	1.50	.75
	100 ft/ 30.5 m	4.15	1.38	.69	4.15	1.38	.69	5.64	1.88	.94
	500 ft/ 152.5 m	4.6	1.56	.78	4.68	1.56	.78	6.35	2.12	1.06
TOTAL**	50 ft/ 15.2 m	20.50	7.00	3.75	11.50	4.00	2.25			
	100 ft/ 30.5 m	37.00	12.75	6.50	21.50	7.50	4.00	———	———	———
	500 ft/ 152.5 m	154.00	52.75	27.50	115.00	41.50	23.00			

The above costs are for dry land jobs, accessible to a truck mounted rig. Drilling on water will be more costly. Table M.8 shows additional costs for drilling over water. (See Section M.2 for calculations and assumptions)

* Details of the included items are presented in Tables M.2 - M.6.

** The total cost - sum of boring and testing costs - is rounded to the nearest $0.25.

*** Incomplete Data

South (Capozzoli & Associates, Inc., 1975)

1) Additional cost per foot--\$2/ft
2) Mobilization and demobilization--10% of additional costs (assumed)
3) Barge (\$35/day) plus tug and crew (\$20/hr--assumed) @ 24 hr/day--\$515/day. (For a drilling rate of 100 ft/day (30.5 m/day), the cost is \$5.15/ft of boring.)

TABLE M.8: ADDITIONAL EXPLORATION COST DUE TO DRILLING OVER WATER (In Dollars/Linear Foot of Tunnel)

BORING DEPTH	BORING SPACING					
	NORTHEAST			SOUTH		
	50 ft (15.2 m)	150 ft (45.8 m)	300 ft (91.5 m)	50 ft (15.2 m)	150 ft (45.8 m)	300 ft (91.5 m)
50 ft (15.2 m)	16.80	5.60	2.80	9.65	3.22	1.61
100 ft (30.5 m)	33.50	11.80	5.60	15.70	5.24	2.62
500 ft (152.5 m)	166.00	55.50	28.70	78.60	26.20	13.10

URBAN BORING COSTS

Because of congestion and special legal rights, drilling within a city normally has at least two (2) additional costs:

1) Drilling permit, \$25/boring
2) Traffic control, \$60/day/man

The main factor controlling the cost increase will be drilling rate, the effect of which cannot be estimated.

As used previously, the assumed rates yield:

Northeast: 40 ft/day (12.2 m/day) traffic control, \$1.50/ft/boring

South: 100 ft/day (30.5 m/day) traffic control, \$0.60 ft/boring

The resulting increase is approximately 10% over that shown in Table M.7. This will no doubt be a lower bound because of problems of disposal of drilling fluid, insurance against breakage of utility lines, etc.

CONE PENETROMETER COSTS

Average boring spacing is rarely less than 50 ft (15.2 m), and therefore large, isolated obstructions may not be detected. To reduce the size and probability of encountering such obstructions, an alternative vertical penetration technique which is cheaper than boring can be used.

The cone penetrometer represents one such alternative. Simple penetration (pushing) will cost on the order of \$3/ft (\$9.80/m), while testing can be performed for \$4.75/ft (Ardaman & Associates, 1975). The mere fact that an obstruction is or is not encountered through penetration is valuable information in itself. By recording the penetration resistance (testing), the record can be an indicator of soil property variations with depth and can yield numerical results through existing correlations.

Typical penetrometer costs are shown in Table M.9. The following assumptions are basic to this table:

1) The lowest two tunnel diameters of the profile were tested (40 ft / 12 m).

2) Mobilization and demobilization is not included. However, these costs are \$200 for urban areas and \$350 over water.

TABLE M.9: ADDITIONAL COSTS OF CONE PENETRATION
(In Dollars per Linear Foot of Tunnel)

	Test Spacing	Hole Depth 50 ft (15.2 m)	100 ft (30.5 m)	200 ft (61 m)	500 ft (152.2 m)
Dry Land	10 ft (3.1 m)	22	37	67	157
	50 ft (15.2 m)	4.40	7.40	13.30	31.40
	150 ft (45.8 m)	1.40	2.40	4.40	10.40
Over Water	10 ft (3.1 m)	32	57	107	257
	50 ft (15.2 m)	6.40	11.40	21.40	51.40
	150 ft (45.8 m)	2.10	3.80	7.10	17.10

ACCURACY AND CONSIDERATIONS OF VERTICAL BORING

When comparing different methods of exploration, relative cost is not the only factor to be considered; reliability of exploration data is also important. The accuracy with which stratification, bedrock depth, soil properties, etc., are established will greatly affect the assessment of risk for design and construction, and therefore project cost.

In any type exploration program, since an infinite sample is required to determine the exact state of nature, the objective is to sample a representative portion of the tunnel alignment, or those areas in which the uncertainty is highest. A vertical boring is an inexpensive method of determining the soil conditions at a point for shallow tunnels. However, such a small percentage of the total tunnel volume is sampled, that sampled conditions must be interpolated or extrapolated to approximate the conditions at any point not on the campled vertical line.

The extrapolation error, common to all limited exploration programs, is an eventual source of construction problems and project cost overruns. Therefore, the ability of various exploration techniques to define possible problem situations, i.e. to reduce extrapolation error, is a measure of their value.

Two types of limitations may reduce the value of vertical borings as an exploration technique--uncertainty of the state of nature between borings, and faults within the technique itself. The first is an interpretation problem wherein troublesome tunneling problems may not be detected; these are rock pinnacles and correct boulder size and frequency and small lenses of running ground. The second limitation involves the difficulty of obtaining reliable physical parameters with present boring techniques. Lack of precise correlations between index tests and properties, sample disturbance and numerous testing problems often lead to conservative and therefore costly design. Another problem that may be encountered in deep boreholes ($>$125 ft) is that of hole deviation from the vertical. If the location of a specific problem area must be known within a few feet, the borehole drift angle and direction must be known within a few feet, the borehole drift angle and direction must be known. Overall, however, the interpolation or extrapolation errors far outweigh the technical difficulties.

Once the exploration cost has been estimated, the reliability or accuracy of the costs should be determined. For verification of the boring costs in the Northeast, a "straw bid" was sought from a local drilling contractor (Al Shiner Test Borings, Melrose, Mass.). Calculations from their unit prices were 29% lower than the estimated costs. The difference is in part due to statistical variation, the bidders' low overhead, and the recession. Consequently, the estimated boring cost is felt to be reasonably accurate. As previously mentioned, the latest unit prices for lab testing were obtained from several consulting firms, then

averaged. However, since testing is less than 16% of the total exploration costs, except in the South where drilling is much cheaper, periodic price changes or statistical variation will not appreciably affect the total cost.

M.3 SURFACE GEOPHYSICAL EXPLORATION: COSTS AND CONSIDERATIONS

SURFACE GEOPHYSICAL EXPLORATION COSTS

Information on applicable surface and borehole geophysics methods was obtained from Weston Geophysical Engineers, Geophysical Survey Systems, and Holosonics. The costs obtained from these sources are very similar for equivalent methods, and hence the summary presented here will be by method.

The cost per foot of the surface geophysics methods are shown in Table M.10. These costs assume a 1 to 2 mile (1.6 to 3.2 Km) tunnel length and that some cross-profiling would be done in addition to centerline profiling. A typical tunnel investigation will most likely require a minimum of three times the tunnel length in actual profile coverage and may require as much as ten times the length in coverage for a detailed investigation. Obviously, the greater the coverage, the less the risk of encountering unanticipated conditions in the actual tunnel construction.

TABLE M.10: COST OF SURFACE GEOPHYSICS METHODS (In Dollars per Foot and Dollars per Meter)

Method	On Land $/ft ($/m)	Underwater $/ft ($/m)
Seismic Refraction	.75-1.50 (2.50-5.00)	1.00-2.00 (3.30-6.60)
Seismic Reflection	1.00-3.00 (3.30-9.90)	.75-1.25 (2.50-4.00)
Electrical Resistivity	.50-.75 (1.60-2.50)	1.00-? (3.30-)
Electromagnetic Profiling	2.00 (6.60)	

REFRACTION SURVEY CONSIDERATIONS

For many tunnel exploration programs, the refraction profiling of an interface at depth (such as the surface of bedrock at depths from 0 to 500 feet below ground surface) is of particular interest. In areas where subsurface interfaces are nearly planar, interpretation of data is highly reliable and a minimum of correlation borings are required.

Where conditions vary laterally, interfaces are irregular, or thin layers occur, the degree of reliability decreases. The usage of crosslines and existence of velocity contrasts between layers of approximately 1 - 1.5+ are desirable to improve data reliability. Since this technique requires relatively long lines, usually on the order of 3 to 10 times the depth of penetration and geophone spacings up to 100 ft (30 m), the method can be looked upon to some extent as an averaging technique.

A usual norm for predicting refraction survey accuracy is a variation of ± 10% from actual; that is, a depth reported from a seismic survey line should agree within 90 to 110% of the depth disclosed during excavation.

Two limitations can substantially affect the 10% accuracy. The first is the "blind zone" condition in which a relatively thin intermediate velocity layer such as dense glacial till, weakly cemented material, or a weathered rock zone overlie hard bedrock. In such cases, the hard bedrock will be "seen" and not the blind zone. (Refer to Soske, 1959, for further discussion.) Figure 3.10 schematically shows the blind zone. Athough the depth error could be considerable, this error condition can be recognized by a limited correlation boring program if the layer is continuous. Discontinuous layers or boulders will be difficult to find without extensive vertical boring programs. Note the advantages of horizontal hole exploration.

The second limitation concerns a shallow or intermediate depth, high velocity zone of limited thickness; in this condition, refractions from the underlying, high-velocity rock at depth are masked by the wave propagation through and from the thin layer. In this set of conditions, as with the previous, a correlation boring program should result in immediate recognition of this problem if the layer is continuous. Again, if it is not recognized, the geophysical methods can become unreliable.

Irregularities of rock interfaces are a further source of profiling errors; the effect of this condition can be minimized by closer line spacing and boring control.

REFLECTION SURVEY CONSIDERATIONS

High-resolution methods of seismic reflection profiling for underwater exploration have resulted in widespread usage of this technique for river, harbor, and other water-covered areas. Since the source and detector are maintained in close proximity to one another, the incident energy is nearly vertical; high resolution is obtained and continuous recording of sub-bottom interfaces results.

Because of the high resolution nature of this method, accuracy of interface profiling is usually on the order of a few percent of actual, if accurate velocity information is available (either by assumption or based on seismic refraction measurements).

Since only reflected travel-times are measured, two possible problems are encountered with this method: (1) the identification of reflecting horizons, and (2) the depth calculations based on assumed velocities. The reflecting horizons are usually identified by correlation with boring data and/or refraction velocity measurements. This correlation is especially necessary when the limit of penetration is at or above a proposed tunnel-grade alignment. The depth errors based on incorrectly assumed velocity values are directly proportional to the percentage differences from the assumed value of 5000 ft/sec (1500 m/sec). Reflection profiling on land is generally not suitable for depth penetrations less than 600 ft (183 m).

ELECTROMAGNETIC SURVEY CONSIDERATIONS

See Section 4.3.

VERTICAL BOREHOLE GEOPHYSICS: COSTS AND CONSIDERATIONS

The cost per foot of the borehole geophysics methods are shown in Table M.11. These again assume a tunnel length of 1 to mi (1.6-3.2 km). Note that in many cases, the boreholes might already exist from preliminary survey work, and thus the additional cost for the geophysics is very small.

TABLE M.11: COST OF VERTICAL BOREHOLE GEOPHYSICS
Tunnel Length = 5000 ft

Depth of Holes (ft)	Spacing of Holes (ft)	Geophysical Logging Cost	Borehole Cost	Cost Per Foot of Tunnel w/Borings	Cost Per Foot of Tunnel w/out Borings
100	100	$27,500	$107,500	$ 27.00	$5.50
	250	15,000	37,350	N.A.	
500	100	47,500	487,500	107.00	9.50
	250	25,000	169,000	N.A.	

(1 ft. = 0.305 m)

APPENDIX N

CERRITOS CHANNEL CROSSING: A DETAILED OPERATIONAL STUDY [1]

N.1 INTRODUCTION

The directionally-controlled, horizontal drilling techniques used to cross the Cerritos Channel, Long Beach, California, were developed by Titan Contractors Corp. of Sacramento, California.[1] Since 1966 Titan Contractors has been engaged in horizontal boring contract work for short distance underground road and other crossings. The development of long distance methods has been a logical step for Titan. Distances of 1000-1600 ft (305-488 m) in soft ground are achievable with their available equipment. Development is continuing.

Through trial and modification of Titan's conventional road boring equipment, Martin Cherrington, the company's founder, had determined that the equipment and methods involved in oil well drilling were necessary for horizontal boring and soft ground. Myron Emery, through his experience with Dyna-Drill in downhole drilling motors and directional surveying and control for oil well drilling, contributed significantly to the design of the drilling systems and methods. The cooperation of these two individuals has produced a workable system for drilled pipeline installation.

The Titan Contractor's horizontal directional drilling is dependent on three pieces of equipment, a 1 3/4 in. (4.4 cm) diameter Dyna-Drill, a directional survey or navigation instrument, and a drill rig. Each piece is dependent on the other for a successful directional drilling system. The system components had all been assembled on the basis of Myron Emery's and Martin Cherrington's experience in drilling. As a complete system, this equipment has completed 7 river crossings of 6600 ft (2013 m) aggregate length (including the Cerritos Channel). THIS METHODOLOGY IS INCLUDED IN A PATENT-APPLICATION AND THIS PUBLICATION DOES NOT IMPLY A RELEASE OF PATENT RIGHTS.

The Dyna-Drill, a 1 3/4 in. "micro-slim" unit (shown schematically in Figure D.2 and operationally in Figure N.1) was selected for its directional drilling characteristics. The design, referred to as a downhole drill motor, allows rotation of the drill bit only. The drill string remains stationary. A bent housing and provisions for mounting various deflection shoes have been incorporated into the design. See Appendix D for details of equipment.

Because the drill string does not rotate during drilling, the orientation of the bent housing and deflection pad can always be determined. Correspondingly the direction of movement of the bit during drilling can

[1] Contents of this chapter were supplied by Titan Contractors. Citation of this example does not imply endorsement by DOT, FHWA or MIT.

BIG ALICE - TITANS HORIZONTAL DRILLING RIG

DYNA DRILL, BENT HOUSING W/PAD, WASHOVER

FIGURE N.1
MANDREL SYSTEM - CONCEPT, FIELD DEPLOYMENT
(PHOTOS COURTESY OF TITAN CONTRACTORS)

be controlled; the chief unknown is the rate of change in direction. Other benefits are also present; wear on the outside face of the drill pipe is reduced and the cyclic stresses occurring when a curved drill string is rotated are eliminated. A high bit rotation speed of 800-1200 rpm allows rapid drilling rates. Also the small weight decreases the tendency for downward drift. One drawback of a small Dyna-Drill is the low torque available at the bit--8.8 ft-lbs (11.9 Nm). In hard and gravelly materials, progress is slowed considerably over rotary drilling rates. Jamming may occur.

The second critical piece of equipment is the directional survey or navigation instrument. The instrument used by Titan Incorporated, consists of a single frame camera to acquire data from a magnetic and gravity field sensitive instrument. This and other navigation units are compared in Table E.1. The unit is manufactured by Sperry-Sun Corporation of Houston, Texas. Capable of being pumped down the "pilot" bore BQ drill pipe (2 1/8 in. (5.4 cm) O.D., 1 7/8 in. (4.8 cm) I.D.), the survey instrument records the direction and angle of the drill pipe at the bottom of the BQ drill string (just behind the Dyna-Drill). By measuring the orientation of the bit with the instrument at the approximate intervals of 30 ft (9.2 m), the path of the drill hole may be plotted by angle change and distance computations. Control of the bit under conditions of <u>constant</u> magnetic fields can be thus achieved and, as a result, precise control of the exit point and the path of the pilot bore is available. Accuracies of +10 to 20 ft (3 to 6 m) in 700 ft (213.5 m) had been obtained on previous projects.

The final critical element for the installation process is "Big Alice," the drill rig shown in Figure N.1. Initially Titan utilized horizontal short-distance road-boring rigs to rotate and push the drill pipe into the ground. Within the last year, however, a larger single purpose machine was built from purchased components on the basis of experiences with the smaller rigs. This current drill rig incorporated all its power and power transmission units onto a traveling carriage supported by a frame allowing approximately 45 ft (13.7 m) of travel. By attaching legs at the rear and changing other geometry, the frame may be positioned at the correct initial driving angle required by the conditions present at a specific site. The carriage provides the power to place successive sections of 30 ft (9.2 m) long drill pipe. The machine is constantly being modified as conditions and experiences dictate.

Only the pilot bore excavation of the pipe line installation will be discussed in this appendix. Since a move was required to complete the Cerritos Channel crossing, the economic calculations will be based upon anticipated conditions to simplify presentation. The remainder of the appendix will be divided into two main sections: Original Project Planning (N.2) and Methodology for Horizontal Boring (N.3). Included in the projected planning section will be: project strategy, scheduling, anticipated problems, labor requirements, bidding strategy and climate, cost analysis, and required permits; whereas the methodology section

will include discussion of mobilization steps, preoperational checks, operating methods, washover, labor deployment and example times for drilling cycles.

N.2 ORIGINAL PROJECT PLANNING

PROJECT LOCATION

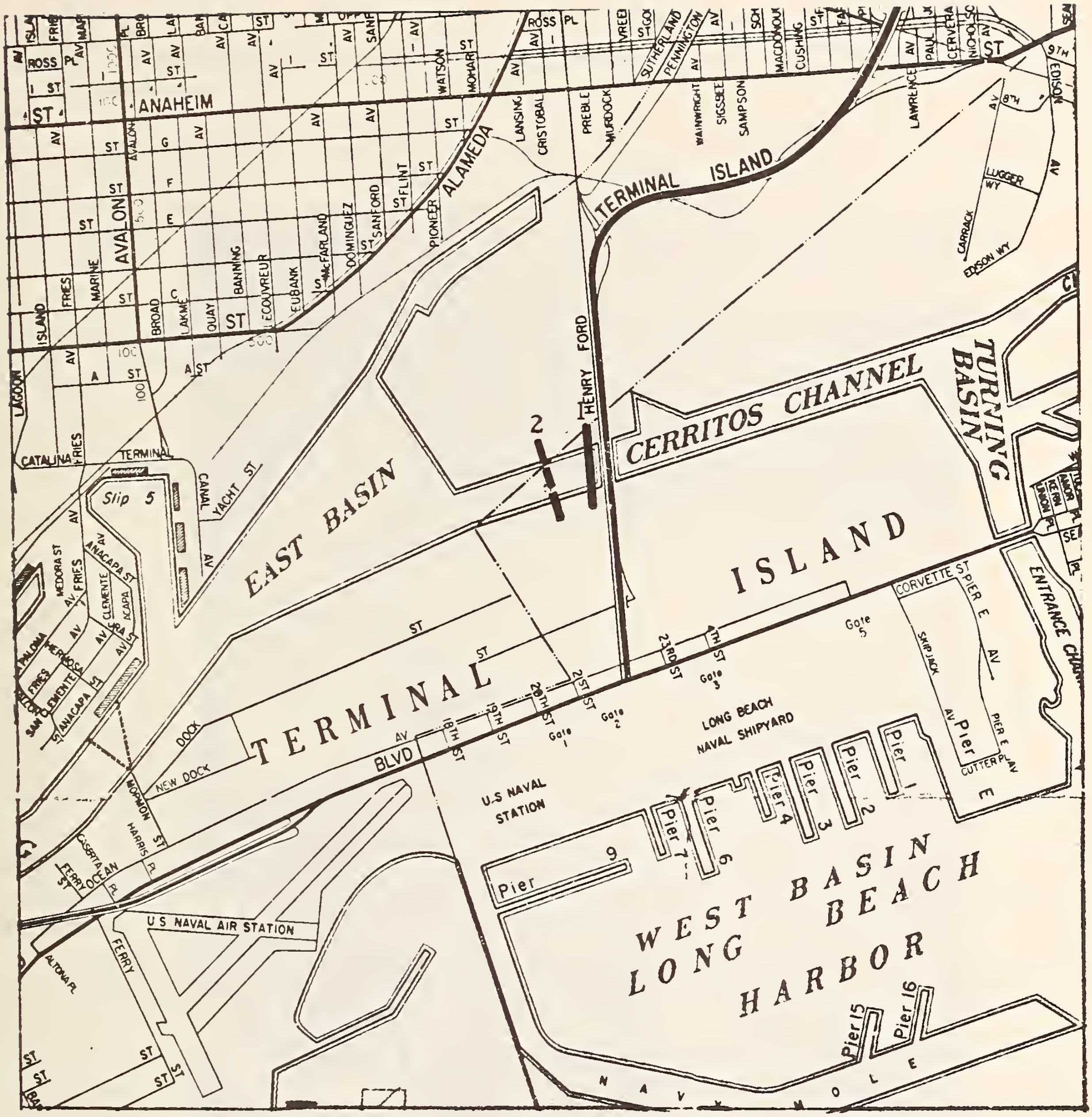
The project was located on Terminal Island in Long Beach, California, as shown in Figure N.2. The first pipeline alignment as illustrated in Figures N.2 and N.3 was 50 ft (15 m) west and parallel to the center line of Henry Ford Avenue at the Cerritos Channel drawbridge. As shown in Figure N.4, the planned horizontal length of the crossing was estimated at 1126 ft (343 m). The maximum depth at the center point was 160 ft (49 m) below mean low water.

Titan Contractors had initially been requested by Dow Chemical in early 1974 to install a casing large enough to nest two 4-in. (10.2 cm) product lines and have room for a possible third 4-in. line. The method of installation was especially important to Dow because of two restrictions of the site (shown in Figure N.4): (1) Two rows of sheet pile extended across the property to an unknown but estimated depth of 65 ft (19.8 m) below mean low water and (2) The existing ground surface elevation behind the dikes and sheet pile walls on both sides of the channel was as low as 6 ft (2 m) below mean low water in the channel. A dredged or bridged crossing here would entail high costs of construction as well as possible high costs and delays for preparation and approval of an environmental impact statement.

PROJECT STRATEGY

To prepare a bid Titan developed their own strategy, analyzed the site for a suitable crossing location and developed a proposed crossing path. The initial plan for the crossing included an entry angle of 26 degrees and an estimated elevation below mean low water mid-point of the crossing of - 160 ft (49 m). This geometry was dictated by the two rows of sheet pile wall to be crossed. Based on this estimate, Titan's geometry allowed 65 ft (19.8 m) plus 10 ft (3.1 m) (necessary clearance that Titan desired) plus 5 ft (1.5 m) (contingency) or 80 ft (24.4 m) below mean low water at the innermost sheet pile wall.

Another important input into the geometry was the maximum build angle. Build angle is defined as the rate of change in vertical angle of the drill string and is illustrated in Figure G.11. Titan's experience has shown that a build angle of 5 degrees per 100 ft (30.5 m) (used at the Cerritos crossing) is satisfactory. The main restriction is the size and strength of the pipeline being installed. For large build angles, 10° per 100 ft (30.5 m) and above, it becomes difficult to transmit full axial thrust from the drill rig to the bit, especially in softer formations. Build angles of up to 26 degrees per 100 ft (30.5 m) have been experienced during pilot hole drilling (with BQ drill



1 ——— First attempt

2 — — — Completed

FIGURE N.2
CERRITOS CHANNEL CROSSING LOCATION
(After Mitock, 1973)

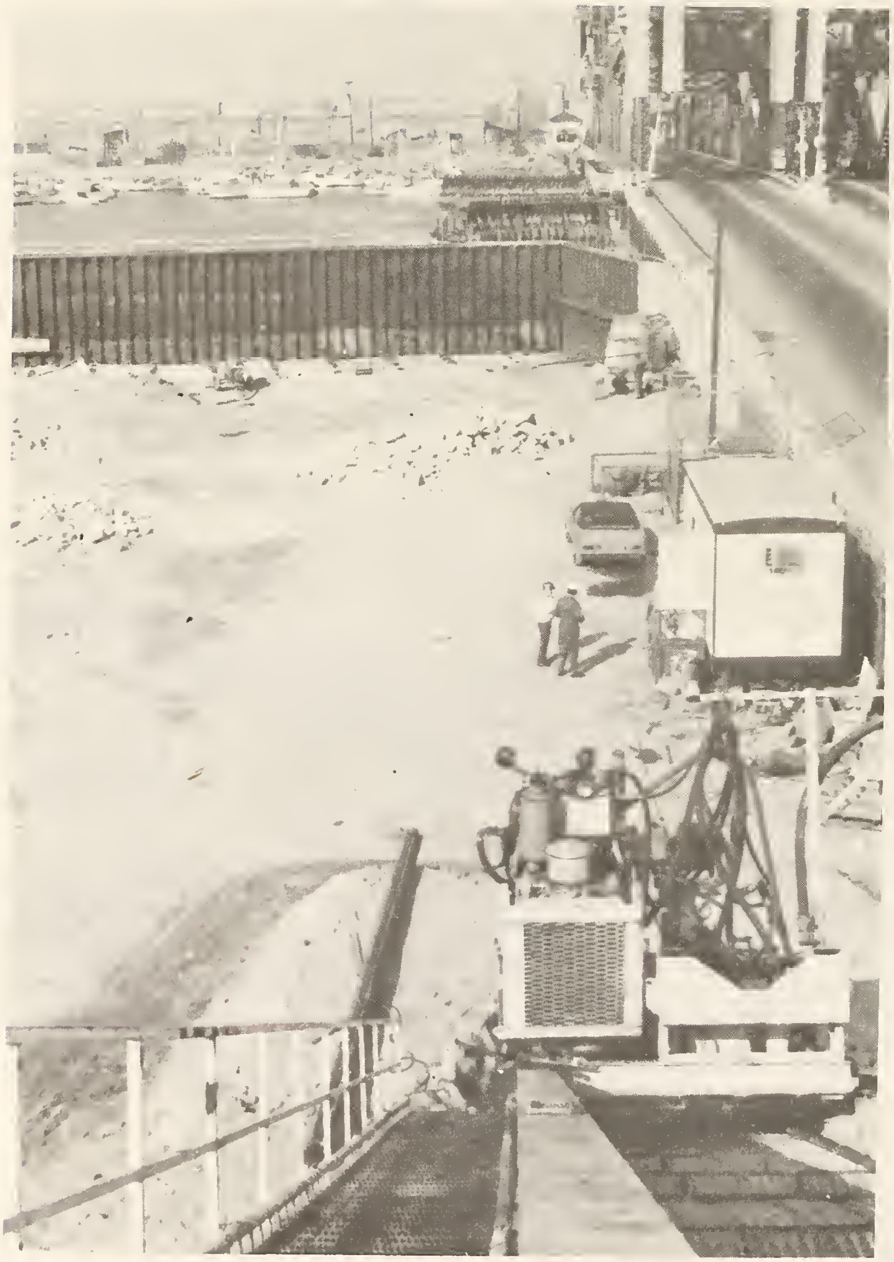


FIGURE N. 3
VIEW OF THE INITIAL PATH FROM TOP OF DRILL PLATFORM

pipe). But these build rates are unacceptable for a completed pipeline installation.

The decision to locate 50 ft (15.2 m) from the center line of Henry Ford Avenue was made on the basis of availability of utilities at that location (water, electric, telephone). This location was preferred by Dow Chemical as well. As will be discussed later, this location had to be changed.

The plan to begin the crossing on the south side of the channel was dictated by the conditions at the planned exit point. A very cramped, 100 x 200 ft (30.5 x 61 m), working area on the north side was available. High tension wires, limited right-of-way and access, and a confidence that the drill heading could be maintained to bring the drill string in on target and avoid the obstacles (oil well and water line in Figure N.4) led to Titan's decision to begin on the south side.

Three phases of work were required for the completed pipeline installation across the Cerritos channel: (1) The pilot hole, (2) The reaming operation, and (3) The installation of the product lines. The pilot hole involves the initial drilling of the 2 1/8 in. (5.4 cm) BQ drill string and its 3 1/2 in. (8.9 cm) "washover" along the entire crossing length. Figure N.1 shows the relative BQ and washover geometry. The BQ drill pipe allows sufficient flexibility for the changes in direction required to maintain the drill string in the proposed alignment. The smaller drill pipe acts as a guide for the higher strength 3½ in. (8.9 cm) drill pipe washover used to reduce the frictional resistance between the BQ drill pipe and the soil. The 3½ in. (8.9 cm) drill pipe is referred to as a washover since the method of placement consists of drilling this drill pipe over the top of the smaller BQ drill pipe as shown in Figure 5.

The reaming and installation of product lines will not be discussed since they are not relevant to exploration.

According to the original plan, the first 140 ft (43 m) a 2 3/4 in. (7 cm) pilot hole would be drilled with conventional rotary drilling techniques and BQ drill pipe. Upon completion of this section, the entire drill string would be removed from the hole. The rotary bit and bit sub would be removed and replaced by a 1 3/4 in. (4.4 cm) O.D. Dyna-Drill (the maximum available bent housing, 0^{o} 45 minutes, was chosen). The now non-rotating drill string would be inserted and drilling would continue with directional control to follow the planned course. When difficulty in orientation or turning of the drill string occurred or when the pushing force required caused buckling of the drill rod (estimated to be 400-600 ft (122-183 m) of penetration) drilling would stop. The drill rig would then be converted to handle 3½ in. (8.9 cm) drill pipe (2 15/16 I.D.) which would then be "washed over" the 2 1/8 in. (5.4 cm) to within 50 ft (15.2 m) of the Dyna-Drill and the bit. The BQ drill pipe—Dyna-Drill combination and the 3½ in. (8.9 cm) "washover" then would be alternately advanced as conditions allowed. The washover would always trail at least 50 ft (15.2 m) behind the bit.

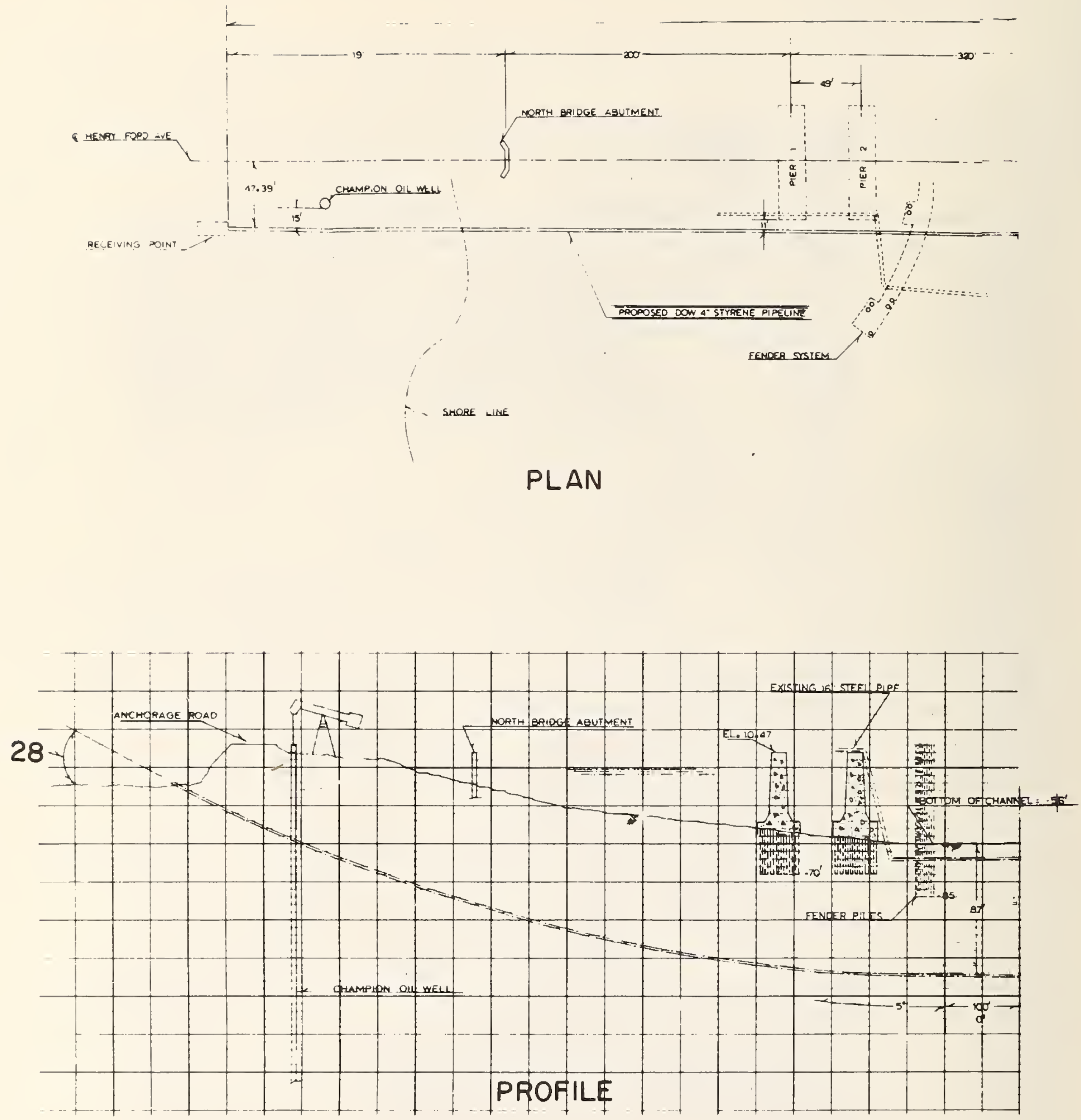
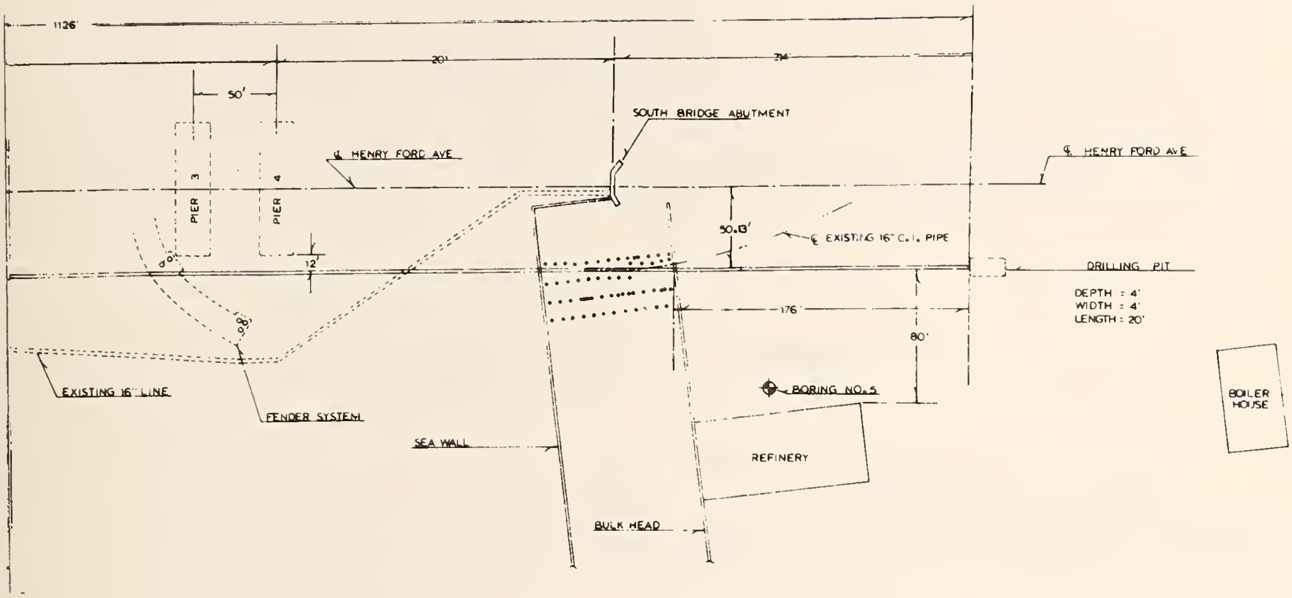


FIGURE N.4 a

NOTHERN HALF

CERRITOS CHANNEL CROSSING PLAN AND PROFILE

(After Titan Contractors, 1973)



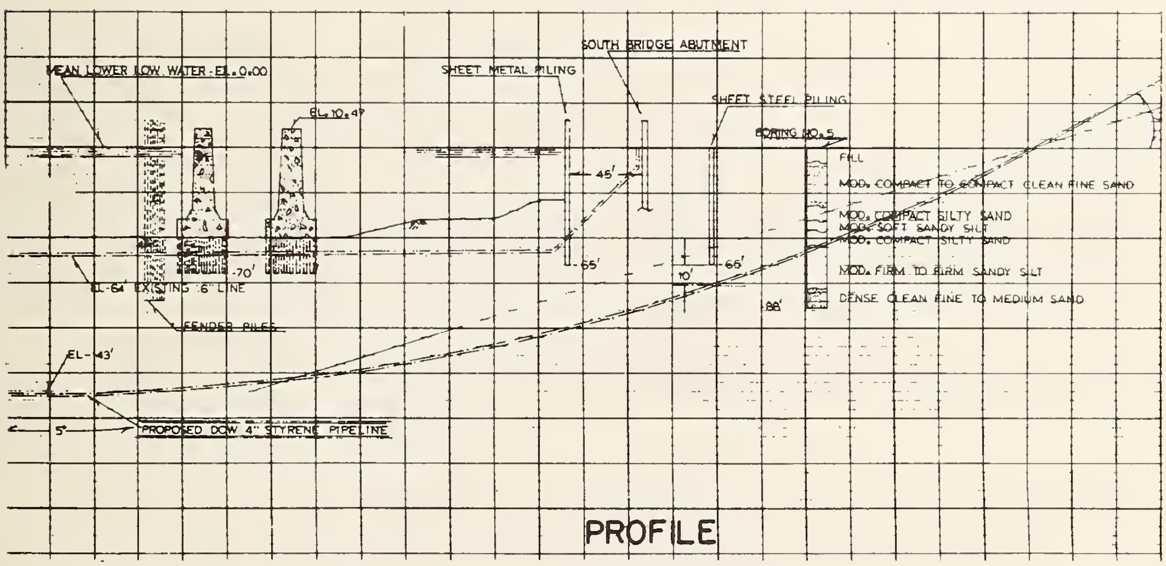


FIGURE N.4 b

SOUTHERN HALF

CERRITOS CHANNEL CROSSING PLAN AND PROFILE

(After Titan Contractors, 1973)

(1 in. = 2.54 cm 1 ft. = 0.305 m)

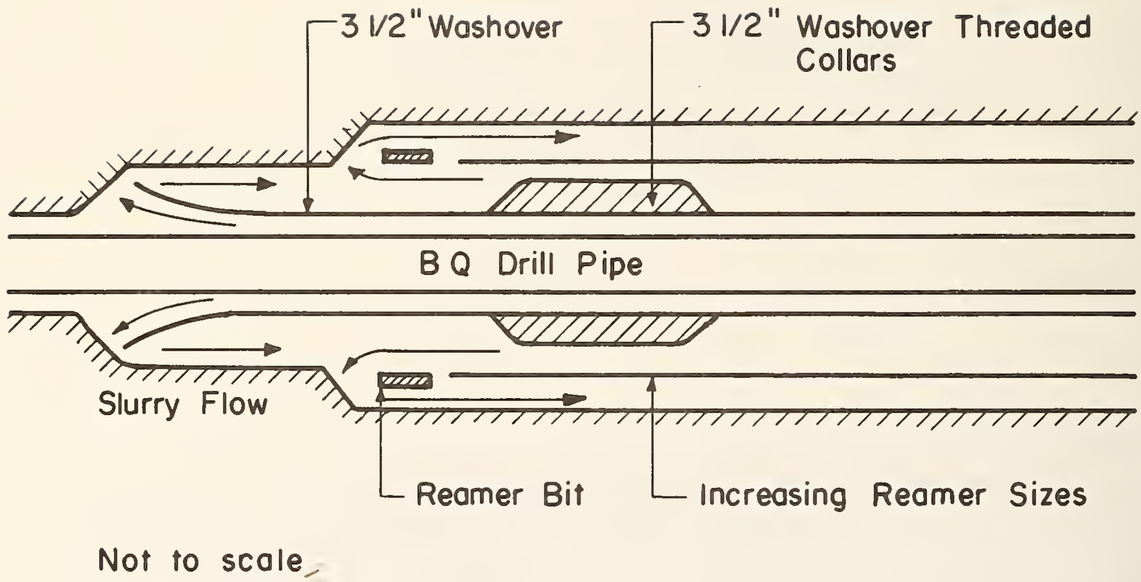


FIGURE N.5 WASHOVER DRILLING CONFIGURATION (SCHEMATIC)

(1 in. = 2.54 cm)

SCHEDULE

The initial schedule was developed with the planned strategy and previous experience in the clay-silt soil of Louisiana and the sandy soils of California. Titan's experience in sandy material was based on the use of a smaller drill rig to push the same 1 3/4 in. (4.4 cm) Dyna-Drill; however, penetrated distances were less than 700 ft (213 m). The following was the initial schedule used to prepare a bid proposal.

1. Site Set-up and Mobilization
   One shift (12 hours) . . . . 5 days
2. Pilot Hole and 3½-inch Washover
   One shift (12 hours) . . . . 7 days
3. 12-inch Casing
   Two shifts (24 hours) . . . . 6 days
4. Product Line Installation
   One shift (12 hours) . . . . 5 days
5. Site Cleanup
   One shift (12 hours) . . . . 2 days
6. Demobilization
   One shift (12 hours) . . . . 3 days

Other considerations were made during the project planning phase by Titan because of physical limitations of the site and concerns of others involved with the project. The project site, in this case, presented problems because of the elevation of existing ground. All the entrance and exit points of the pipeline as well as the entire island area was as low as 8 ft (2.5 m) lower than mean low water in the Cerritos Channel. The project, originally scheduled for the spring of 1974, was delayed by the low land elevation until January, 1975, in acquiring rights-of-way. Other nearby property owners and the Champlin Oil Company, the property owner at the proposed pipeline exit point, had great concern for potential damages to oil well equipment and possible flooding of the nearby oil fields. The damages could have been large. Titan Contractors and Dow Chemical had to respond to these concerns by taking various precautions, obtaining the required insurance, and providing guarantees.

To prevent flooding, Titan constructed a 6-ft (1.8 m) high earth berm, through which the drill pipe entered the ground. Also a 50-ft (15.2 m) length of 12-in. (30.5 cm) diameter casing and 5-in. (12.7 cm) pipe center was installed near the entrance to provide waterproof casing and a guide and stabilizer for the drill pipe as it was inserted and removed from the drill hole. The required 26 degree entrance angle, shown in Figure N.1, was obtained by setting the toe of the rig on the berm and founding the legs one foot below existing grade.

ANTICIPATED PROBLEMS

A few problems were anticipated by Titan while planning the project. Only one boring, shown in Figure N.4, had been obtained near the path of the pipeline. The indicated combinations of sand and silt were known to have a potential for being soft enough to prevent the Dyna-Drill from building angle as required. Boulders and gravel were known to be present by people familiar with nearby oil well drilling. These materials would present obvious difficulties to achieving reasonable daily production as well as requiring frequent changes of the bit (requiring withdrawal of the entire drill string). A soft layer would cause serious problems since Titan's directional drilling is dependent on a deflection shoe bearing on the side of the hole for any angle changes. The drill string may be pulled back, reoriented, and reinserted in the hope of locating a suitable hard layer that would permit building angle (a very simple and routine measure used when the Dyna-Drill progresses off course.)

Another serious unknown was the effect of the large quantities of iron (the two sheet pile walls, water lines, and oil wells) on the magnetic survey tools. Magnetic north, as perceived by the survey tool, would be drawn in direction of an iron concentration. Essentially, if this occurred, Titan would be drilling toward a local magnetic field while believing they were on target. This problem was assumed solvable by Titan since they would be 160 ft (49 m) below mean low water at the crossing midpoint, and away from all important sources of magnetic interference. However, the bridge seriously interfered with navigation and was one of the factors which required relocation.

LABOR REQUIREMENTS

Three skilled people, the operator of the drilling rig, the supervisor, and the drilling engineer, are basic to the operation. The operator has complete responsibility and control over the operation when drilling is underway. A minimum of three years drilling experience is recommended by Titan. The operator must be able to accurately read the drill bit progress by watching pressure guages and by sensing the reactions of the rig from the normal force and rotation imposed on the drilling rod as the drill bit is advanced. He must be able to determine accurately the formation hardness and characteristics as well as drilling mud pressures at the bit. During drilling he is completely responsible for any damages that occur to the drill string and bit.

The drilling engineer, Myron Emery in this case, is responsible for the direction and path the bit takes during drilling. The drilling supervisor, Martin Cherrington, is responsible for efficiency of the operation, general trouble-shooting, and problem solving. The drilling engineer's position requires a minimum of two to three years' experience. The drilling supervisor's position requires five years' experience. Both positions require experience and knowledge in the areas of machinery and hydraulics, surveying, fluid mechanics, mud treatment, and procedures and theory of directional drilling.

Other personnel are required as the project progresses. The mud mixer, the chuck tender, the laborers, the crane helper, and the welder's helper are needed for some if not all job phases. Titan recommends these people have at least two years' experience in their area of work.

While the labor crew at Long Beach was both union and non-union with much previous experience in some areas of the country, union rules require local inexperienced crews on a project. Experience had shown a union concern to have workers on the job even though they did nothing but put their time in. Featherbedding requirements by the union halls have been an important problem. Most of the men supplied by the union halls have been unskilled in this type of operation and had to be hired though not put to work. Titan anticipated no such problem at Long Beach.

BIDDING STRATEGY AND CLIMATE

Titan Contractors, with a unique and novel method of pipeline installation, have been using each of their projects as research and development tools and opportunities to gain experience in various soil conditions and job situations. Their drill rig and technology is still in an early stage of development. Only five projects have been completed with their large drill rig (that used at the Cerritos Channel crossing) and current methodology. Their competitors have been the conventional methodologies such as dredged or bridged crossings. Such is the climate in which Titan Contractors operate.

In preparation of the bid proposal to Dow Chemical, Titan had developed cost estimates based on their most recent previous experiences in Louisiana and some earlier experiences with a smaller drill rig in California. The materials in Louisiana and at Long Beach were both fine soils, silt— sand in Long Beach and clay— silt in Louisiana. It appears that Titan assumed both soils were similar enough to use the same strategy and time requirements for planning the installation at Long Beach. The project strategy at both locations was initially similar.

As drilling progressed at the Cerritos Channel crossing, Titan was to discover a more granular, less cohesive material that would drastically change the initial plans. Some uncertainty of soil conditions was realized by Titan. A contingency had been added to the bid proposal to cover such unexpected conditions.

The resultant bid proposal submitted to Dow Chemical for the Long Beach project included a cost of approximately $250,000. This price included (1) the engineering design of the crossing, (2) all materials and supplies including casing and product lines, and (3) the installation of these materials.

COST ANALYSIS

The following is a summary of a cost estimate prepared for the Cerritos Channel Project as planned to isolate the costs of pilot hole excavation. This analysis is based on cost information available before the project was completed. The strategy and time schedule used are those developed before the project began.

Mobilization, Demobilization and Cleanup Costs

Labor	$14,180	
Rentals	2,200	
Miscellaneous Expenses	5,750	
Heavy Hauling	11,550	
Sub Total	$33,680	
Overhead	3,370	
Total		$37,050

Pilot Hole and 3½ Inch Washover Costs

Labor	$ 9,920	
Rental	10,980	
Owned Equipment	10,150	
Slurry	1,600	
Miscellaneous Expenses	5,225	
Sub Total	$34,270	
Overhead	3,430	
Total		$37,700

Casing Installation

Labor	$26,620	
Rental	14,500	
Owned Equipment	20,230	
Slurry	2,400	
Miscellaneous Expenses	8,300	
Sub Total	$73,050	
Overhead	7,210	
Total		$79,260

Subtotal (for: Mobilization, Demobilization and Cleanup Costs; Pilot Hole and 3½ Inch Washover Costs; and Casing Installation)	$154,010
Insurance	16,500
TOTAL COST	$170,510

THE ABOVE ANALYSIS DOES NOT INCLUDE THE FOLLOWING COSTS:

PROFIT

INSTALLATION OF THE PRODUCT LINES

CONTINGENCY

ENGINEERING BY TITAN

MATERIAL COST OF CASING AND PRODUCT PIPELINE

COST OF PERMITS

For Titan's present level of technology and experience, the above is a representative cost estimate given the specific items not included. Titan has proven that with optimum conditions, they are able to drill footages of BQ drill pipe of 500 ft (152 m) per day. However, with less than optimum conditions, unexpected soil conditions or other unplanned-for problems, these costs can easily increase, as they did before completion of the project.

APPROVALS REQUIRED BY ENVIRONMENTAL AND GOVERNMENTAL AGENCIES

Long Beach Harbor Authorities, the Corp of Engineers, the Water Quality Control Board, Planning Commission, and Coastal Zone Commission of California had jurisdiction over the planning and design of the Long Beach installation. A critical component to the approval process was an Environmental Impact Report. Also important on the Long Beach Project was the approval of the Champlin Oil Company who owned the property around the proposed exit point for the pipeline. The approval procedure followed by the Dow Chemical Corporation Long Beach Project is outlined in the paragraphs below.

All data for the proposed project (location, plan view, project size, type and objectives, estimated cost, environmental setting, environmental impacts, etc.) were submitted to the Long Beach Department of City Planning for preparation of an Environment Impact Report. The city prepared all reports for area projects to verify data and promote development. The Environmental Impact Report for this project included not only the Channel Crossing but the whole pipeline and terminal facility.

A request for approval and the Environmental Impact Report would then be presented to the City of Long Beach Planning Department and Harbor Commission. These agencies would submit the information to the Coastal Zone Commission, a state agency, to obtain approval before granting their own approval. Included in this process were public hearings and a review system that analyzed the project's effects on the environment, land use, traffic, and people. Since pipeline and terminal installation would result in no change in land use from the existing, no problems occurred in the approval process. Four months were required for this step.

A permit was required by the Corp of Engineers to cross the waterway. This was quickly obtained since there would be no disturbance of the channel or channel traffic. The permit granted by the Corp of Engineers read as follows: "Permit to construct a 4-inch pipeline with a 12-inch diameter casing by directional drilling (no dredging) under the Cerritos Channel, Pacific Ocean, at about 50 feet west of the centerline of Henry Ford Avenue drawbridge, City of Long Beach, County of Los Angeles, California." Note the emphasis on the non-dredging solution.

The final approval required was that from the California Regional Water Quality Control Board. Their approval was contingent upon approval by all others in the review process. For the horizontal directionally drilled crossing, they asked that the application be withdrawn since no possible change to water quality could result. Their principal concern in a channel crossing project would be disturbance of an approximately ten foot thick layer of material of the channel floor that was contaminated with heavy metals and other toxic materials. Siltation also would be a concern but with horizontal directional drilling no disturbance would result.

The Champlin Oil Company, who owned the right-of-way at the proposed pipeline exit point, caused some delay. They had been deliberate in their actions because of possible high tide flooding of their leveed oil fields on the exit side due to any piping or blow out problems caused by Titan's installation. Champlin had no material benefits to gain from the passage of a pipeline. Their principal concern in granting a right-of-way was the definition of each party's liability--what accident would be attributable to which party? This problem had caused a few months delay.

The duration of the approval sequence for this project was twelve to fifteen months. The four months required for the review of the environmental impact statement and the preparation of that statement were required mainly because the impact of the project included the proposed storage facility along the Cerritos Channel and an entire pipeline system.

The directionally drilled crossing as completed by Titan would have very little if any environmental impact. At no time would the pipeline construction operation or the pipeline come near the channel water. No contaminated sediment would be disturbed. A small amount

of ground surface would be affected. Relatively little noise and other environmentally unacceptable conditions would be generated during or after construction. Because of the minor impact described above, all groups involved in the approval process indicated that no environmental impact statement would be required for the horizontal directionally drilled pipeline crossing of the channel. Only a three- or four-page impact assessment would be needed. The review and approval of this short document would take much less than the four months required for the impact statement (the time required was estimated by Dow to be one month).

N.3 OPERATIONAL METHODOLOGY FOR HORIZONTAL BORING

MOBILIZATION

Titan Contractors first arrived on the Long Beach, California, site in the fall of 1974 after having completed five successful pipeline installations for Dow Chemical in the Atchafalaya Basin in Louisiana (dimensions ranged from a 1685 ft x 5 in. (514 m x 12.7 cm) crossing to a 750 ft x 12 3/4 in. (229 m x 32.4 cm) crossing. The equipment had been brought to Long Beach by flatbed trailer and assembled on site.

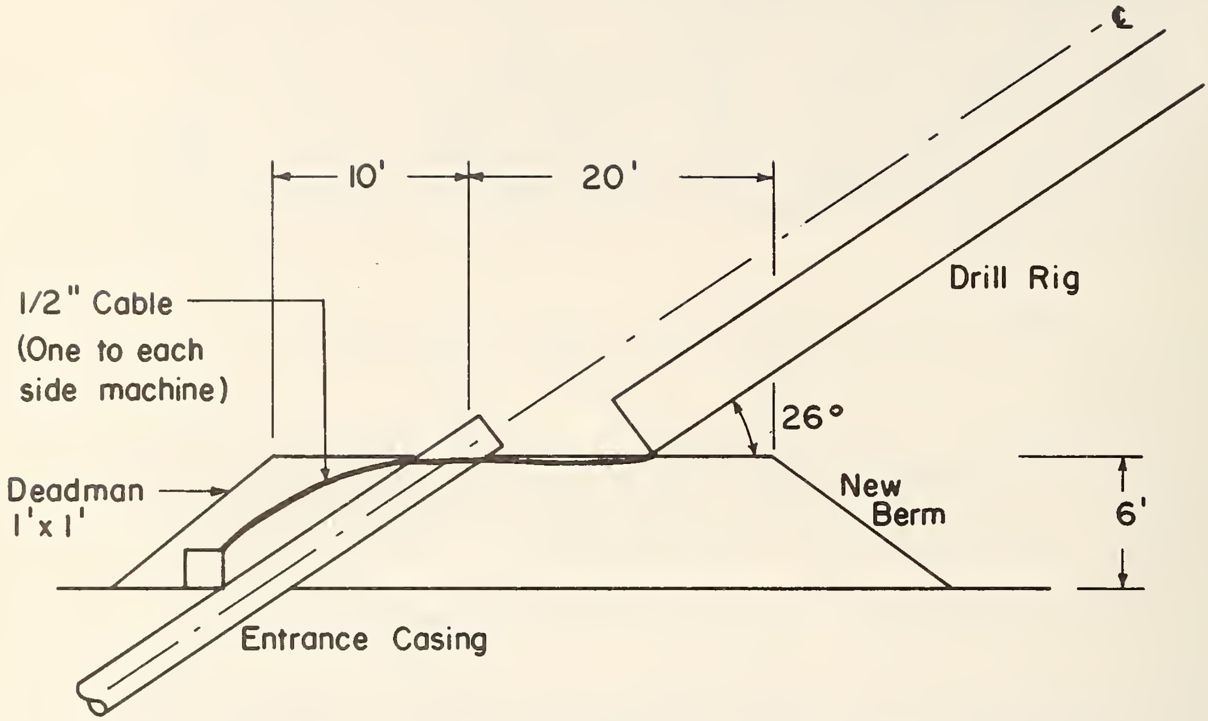
The drill rig assembly and alignment was a major part of the mobilization requirements. The rig was designed for ease of assembly under field conditions. Basically, the disassembled sections of the rig (broken down for transport) are positioned on the ground for partial assembly. The entire rig is raised by crane allowing the sections to fall into final position for assembly. An 80-ton (72.5×10^3 kg) crane or a 25-ton (22.7×10^3 kg) crane can be used depending on the degree of mobility desired for the rig after assembly.

Immediately following the assembly and positioning of the drill rig, the 50-ft (15.2 m) length of 12-in. (30.5 cm) casing, as shown in Figure N.6, was placed to reduce the possibility of flooding and to fix the point of entry of the drill bit and pipe. The project was shut down when this operation was completed while final approvals for the crossing were obtained.

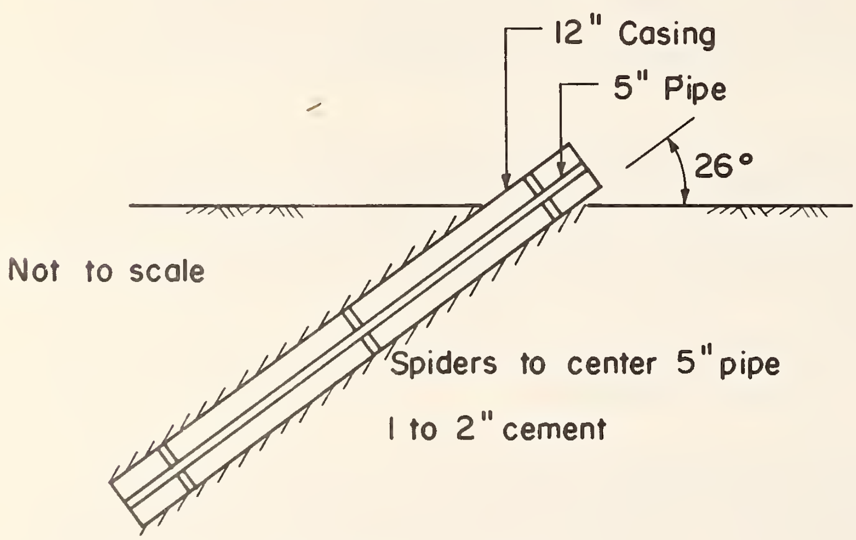
EQUIPMENT REQUIRED FOR DRILLING OPERATION

The drilling operation was begun on Wednesday, January 8, 1975. At that time most of the required equipment was on site; relative positions are shown in Figure N.7. A list of this equipment was as follows:

1. Drill rig
2. Office trailer--8 ft by 20 ft (2.4 m x 6.1 m)
3. Hobart 250 amp welder--machine modification, mobilization and welding of the casing and product line.
4. Allis-Challmers 60 KW-75KVA generator--to power the slurry mix tank and pump.



a) INITIAL CONFIGURATION AT ENTRANCE TO DRILL HOLE



b) CASING AT DRILL HOLE

FIGURE N.6 DRILL RIG ALIGNMENT AND HOLE CONFIGURATION
(1 in. = 2.54 cm; 1 ft. = 0.305 m)

5. IMCO slurry mix tank and pump--to provide mixed slurry to a secondary slurry pump on the drill rig for Dyna-Drill operation or directly to the 3½ in. (8.9 cm) washover pipe.

6. Case 580 loader-backhoe--site preparation, clean-up and any earthmoving requirements of the project.

7. Pettibone Multikrane 15 hydraulic crane--to handle drill steel and casing during drilling operations and miscellaneous lifting chores.

8. Oxygen, acetylene tanks and torches--for fabrication and steel cutting.

9. Miscellaneous replacement parts, hand tools, and equipment.

10. Portable john.

11. 2 1/8 in. (5.4 cm) OD drill rod (BQ)--for pilot hole (preassembled in 30-ft (9.2 m) lengths for faster handling).

12. 3½ in. (8.9 cm) OD drill steel--for washover operations during pilot hole drilling.

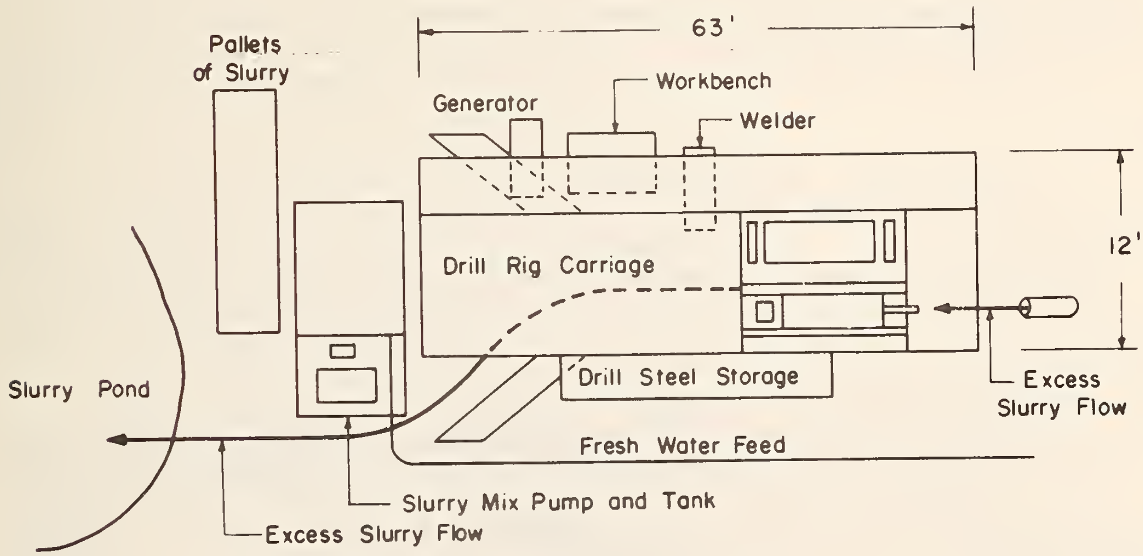


FIGURE N.7 PLAN VIEW OF DRILL RIG AND OPERATION

(1 ft. = 0.305 m)

PREOPERATIONAL CHECKS

Before full drilling operations could begin, several preoperational checks of the equipment were made. The directional survey camera was checked to assure proper alignment and operation. The camera was positioned as close as possible on the center line of the proposed pipelines by sighting in by eye. The horizontal alignment was accomplished with the same methods. It was important at this time to locate the camera as far away as possible from iron objects to eliminate any influences on the instrument's compass unit. However, the area's magnetic fields should be surveyed to ensure uniformity. Once positioned the picture was taken. The photograph was developed and placed in a magnifying reader. A reading of N19½ degrees W and an inclination of about 0 degrees indicated correct operation of the camera since the heading was the same as planned and the survey instrument was set level.

The survey instrument alignment relative to the bent housing of the Dyna-Drill was important also. The survey instrument was positioned on an orienting shoe ("mule shoe") inside the protective casing or survey barrel. To accomplish correct alignment, as illustrated in Figure N.8, the Dyna-Drill, the 10-ft long, 1 3/4 in. sub, and 4-in. long BQ section with the key were assembled. The survey barrel was then positioned with the mule shoe aligned by the key. The survey instrument mounting shoe could then be positioned to give the survey instrument the same relative alignment as the Dyna-Drill bent housing and deflection shoe.

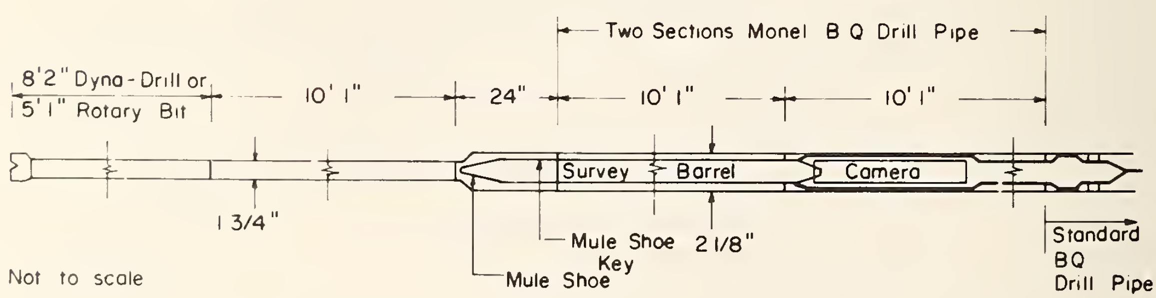


FIGURE N 8 CROSS SECTION OF DRILL ROD NEAR BIT
(With Survey Barrel in Place)

(1 in. = 2.54 cm; 1 ft. = 0.305 m)

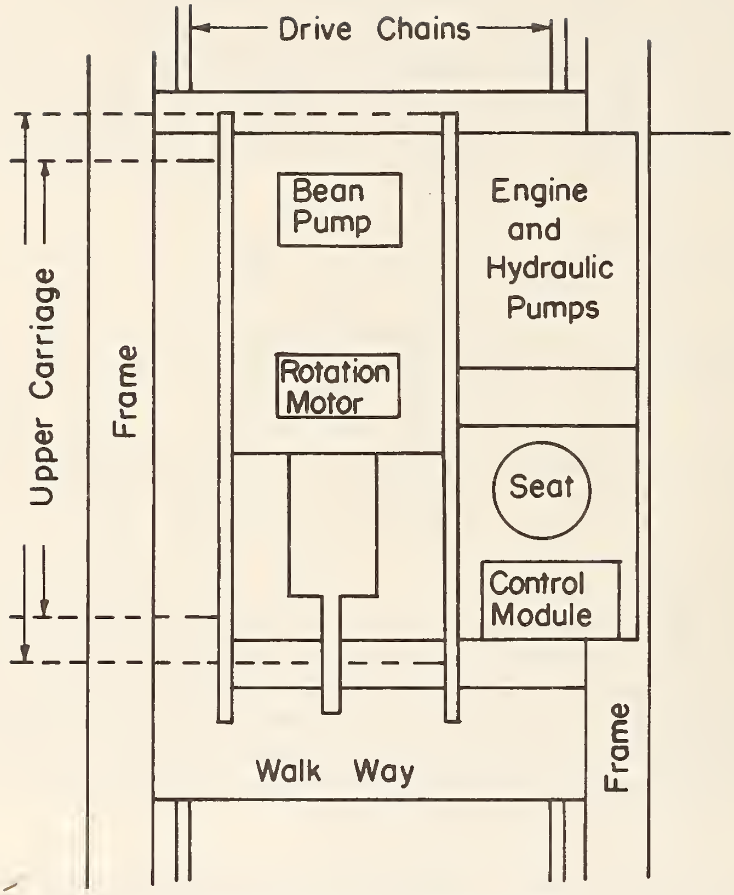
The Dyna-Drill, because of its design requirement of 22 gpm of slurry flow for maximum operational efficiency, required a check of the slurry rate. This was accomplished by positioning the Dyna-Drill prior to drilling, just above the entrance casing. A funnel-shaped pipe section and 90 degree elbow were then placed to catch the slurry flow out of the Dyna-Drill bit and redirect it into a 5 gallon (19 liter) pail. By measuring the time required to provide 5 gallons (19 liters) of slurry, the flow rate could be established and adjusted to the desired rate.

DRILL RIG OPERATION

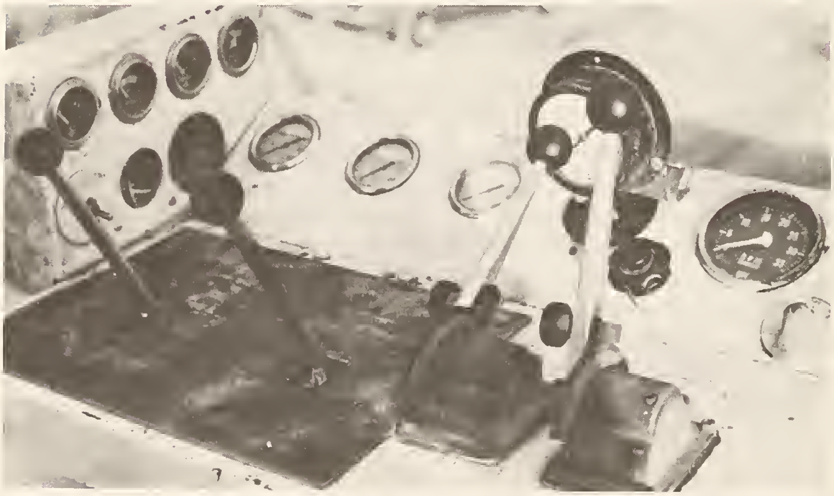
The drill rig is basically designed to push or pull and/or rotate the drill string as job conditions dictate. Most of the push or pull is provided by the two hydraulic motors that engage a drive chain mounted on the frame. This chain can be seen in Figure N.9. These motors normally operate at a pressure of 650 to 700 psi (4.5×10^3 to 4.8×10^3 kN/m^2) when the carriage is moved upward or at 300 to 400 psi (2.1×10^3 to 2.8×10^3 kN/m^2) when the carriage is used to push the BQ washover pipe. When inserting drill pipe of about 500 ft (152 m) in length, only the weight of the carriage is required to supply the necessary normal force. The upper carriage, called out by dotted leaders in Figure N.9, is powered by two hydraulic cylinders when extra pull or push above that available from the hydraulic motors is required. It is also useful when small, precise movements are desired such as when assembling or disassembling the drill rod sections or when moving the Dyna-Drill into contact with a hard object that would easily stall the motor.

The rotation motor is used for many different operations as drilling progresses, including assembly and disassembly of the drill pipe, for rotary drilling, placing washover casing, and for reaming and reorientation during Dyna-Drilling. Clockwise rotation of the motor allowed disassembly of the drill rod. Counter-clockwise rotation was used for all other operations.

During drilling, the operator sitting on the movable carriage has complete control of all operations. He depends on the "feel" of the machine and the sound of the engine as pump pressures and horse power demands fluctuate. This "feel" of the machine is derived from changes in rates of carriage movement and movement of the upper carriage that occurs as the gravity-induced downward force of the equipment on the inclined drill rig frame is overcome by the force on the drill string. Any free play and looseness in the machinery is noticeable as this point is passed. The operator must watch for buckling of the drill pipe in the span from the drill head to the casing (BQ only) occurring at about 2700 lb (12 kN) of axial force (See Appendix G). High side resistance and high tip (bit) forces on the drill string are the cause of axial resistance. The slurry pressure gauge is watched closely during Dyna-Drilling to prevent stallout of the Dyna-Drill or lost time because of no bit contact with the face of the drill



a) DRILL RIG CARRIAGE



b) OPERATOR CONTROL PANNEL

FIGURE N.9 CONFIGURATION OF CONTROL EQUIPMENT (1975)

hole. Stallout of the Dyna-Drill is indicated by high slurry pressures at the pump and the sound of the relief valve at the slurry pump releasing. A stalled Dyna-Drill also increases the possibility of buckling of the drill pipe. The small amount of travel necessary for buckling to occur makes this an important problem. There is no way to determine the proximity of the bit to the face of the hole except for buckling to occur.

The operator also makes use of a solenoid-operated valve (operated by a toggle switch at his left as shown in Figure N.9b) that acts as a brake and prevents carriage movement when he is using the upper carriage for precise movements or when he leaves the machine. The reading shown on the pressure gauge for the travel motors must be increased to 600 to 700 psi (that required from the pump to maintain the carriage stationary on the inclined frame) before activating the valve. Rough engagement and movement occurs if this is not done.

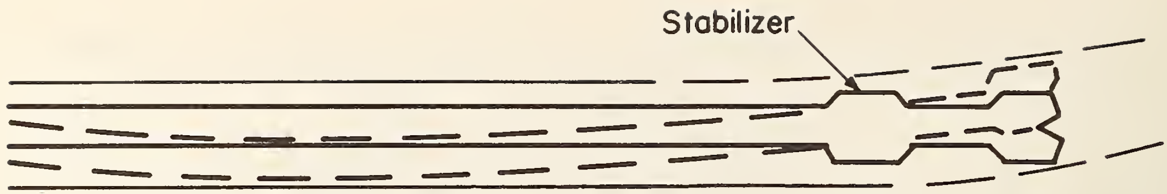
PILOT HOLE--ROTARY DRILLING

The first 140 ft (42.7 m) of hole at Long Beach were rotary drilled. The drilling was accomplished simply and easily by maintaining slurry flow through the rotary bit, back outside the drill pipe and out the entrance of casing while rotation of the pipe occurred. The slurry (which carried the cuttings out of the drill hole and supported the drill hole) was allowed to flow into the low collection area, shown in Figure N.7, for later disposal. Except for some experimentation with recirculation, clean, newly-mixed slurry was used. The high torque available from the rotation motor and a relatively soft soil produced quick progress (about two minutes for each 30 ft (9.2 m) advance).

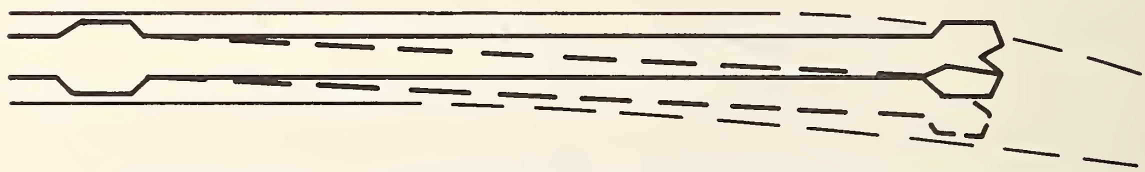
In practice, various lengths and locations of stabilizing collars can provide directional capabilities to a rotary bit. A short illustration of the various arrangements is shown in Figure N.10. The degree of control for this type of directional drilling is low because of a dependence on highly variable axial pushing forces and the density and resistance of the soil being drilled at any particular time. One cannot be sure of the direction the bit will take--left or right--or the rate of upward or downward movement.

PILOT HOLE--DYNA-DRILLING

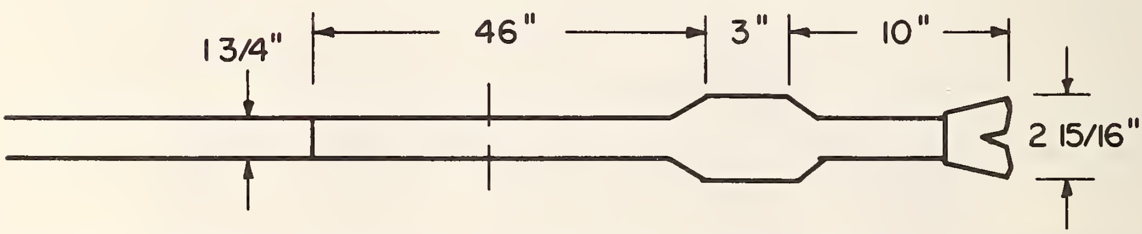
When directional drilling was begun, the rotary bit and bit sub had to be replaced by the Dyna-Drill and its bit sub (shown in Figure N.11). The drill string was removed from the hole while the changes were completed. Also at this time the slurry flow rate must be checked to insure efficient operation--Titan tried for anywhere from 20-25 gpm (0.08 to 0.10 m^3/min); the optimum is 22 gpm. When the correct flow rate was produced, the drill rig operator noted the engine rpm, the hydraulic system pressure (for the slurry pump drive system), and the slurry pressure at the pump from gauges on his control module in order that the desired flow may be maintained during drilling. The



STABILIZER POSITIONED FOR UPWARD DEFLECTION



STABILIZER POSITIONED FOR DOWNWARD DEFLECTION



ROTARY BIT SUB USED BY TITAN IN LONG BEACH, CALIFORNIA

FIGURE N.10 CONFIGURATION OF ROTARY BIT AND SUB

(1 in. = 2.54 cm)

Dyna-Drill and drill string were then inserted into the pilot hole with no rotation or slurry flow. This allowed the bit to follow the previously drilled hole and eliminated starting new holes.

Upon reaching a point within a few feet of the face of the pilot hole, bit rotation and slurry flow was started. The slurry pressure at the uphole gauge was assumed to increase from 350 psi to 500 psi (2.4×10^3 to 3.4×10^3 kN/m^2) due to pressure losses from slurry flow inside and outside the drill pipe 22 gpm (0.08 m^3/min). The resistance to slurry flow from the bit to the ground surface and vice versa outside and inside the drill pipe, causes this pressure increase. With a slurry gauge pressure of 500 psi (3.4×10^3 kN/m^2), the drill bit was pushed slowly on into contact with the face of the hole. While drilling, the pressure on the slurry pressure gauge varies between 500 and 800 psi (3.4×10^3 and 5.5×10^3 kN/m^2). 800 psi (5.5×10^3 kN/m^2) corresponds roughly to the pressure relief valve on the slurry pump.

Theoretically the most efficient pressure for Dyna-Drill operation is 500 psi (3.4×10^3 kN/m^2) (no-load) pressure plus 250 psi (1.7×10^3 kN/m^2) optimum Dyna-Drill differential pressure or 750 psi (5.2×10^3 kN/m^2). But since torque available at the bit--8.8 ft-lbs--is very low, dense sand and gravel materials will easily stall the drill

FIGURE N.11

DYNA - DRILL IN POSITION TO BEGIN DRILLING

motor. As an obstacle or the face of hole is encountered, the slurry pressure will increase from 500 to 800 psi (3.4×10^3 kN/m^2 to 5.5×10^3 kN/m^2) almost instantaneously. If insufficient torque is available to dislodge or cut the obstacle and the Dyna-Drill stalls. Because these obstacles were common in the Long Beach case, the Dyna-Drill would either run at a no load condition away from the face or be stalled against an obstacle at the face of the hole, theoretical slurry pressure for maximum torque output, 750 psi (5.2×10^3 kN/m^2), was impossible to maintain. Harder materials, therefore, require a cyclic advance-pullback technique.

Conditions of high slurry pressure that do not drop when the bit is pulled away from the hole faces also occur. No load slurry pressures reached 750-800 psi (5.2×10^3 to 5.5×10^3 kN/m^2) as restrictions to the annular flow of slurry up-hole from the bit developed (from deposition of cuttings in the drill hole in the space used for return flow of slurry). Pumping may be continued in hopes that the continued high slurry pressures may remove the restriction. However, pumping invariably caused hydraulic fracturing as discussed in Appendix F. Alternatively the drill string can be pulled back to a point where the proper level of no-load pressures exist and the hole redrilled.

The Dyna-Drill may, especially just after entering the pilot hole, become stalled whether the bit is against the face of the hole or away (indicated by slurry pressures of 800 psi (5.5×10^3 kN/m^2) or above). The several possible reasons for this occurence follow.

Reverse fluid flow may have introduced sand particles into the motor. Reverse flow occurs during rapid entry into the drill hole where restrictions around the drill string allow a build-up of slurry pressure at the bit or if hydrostatic pressure inside the drill string is not maintained (by not filling each drill pipe with slurry as it is added to the drill string and pushed into position).

Reverse rotation of the Dyna-Drill also may occur if a flapper valve in the survey barrel did not operate to allow slurry to pass by during instrument removal from the BQ drill pipe. Because of the seals between the survey barrel and the drill pipe wall (to insure that the barrel will be pumped down the drill pipe), a low pressure may be produced on the survey barrel side of the Dyna-Drill if the flapper did not operate. If the differential pressure across the Dyna-Drill reaches 200 psi (1.4×10^3 kN/m^2) or more, reverse rotation may occur, drawing impurities into the motor.

Blockage of the slurry jet holes with hard, packed material or pebbles can be caused by pushing theddrill string with a non-rotating Dyna-Drill or rotary drill. Blockage will stall the Dyna-Drill.

Impurities may settle out of the slurry inside the drill string during entry into the hole or periods of no slurry flow. Restarting the slurry flow will cause this sedimented material to reach the

Dyna-Drill together and stall the motor. This problem can be settled by adequate desanding facilities. See Appendix F for further discussion.

One usually successful method of freeing a stalled or bound Dyna-Drill is to push the drill bit against the face of the pilot hole and rotate the drill string (at less than 5 rpm). All excess slurry pressure is bled off the drill string by the operator before rotation. The bit is then pulled back and slurry pressure impulses or constant pressure is used to force the motor to rotate. This process is repeated and is usually successful. The alternative to this procedure is to withdraw the entire drill string and either clear the bit or replace the motor. (The motor is serviced and repaired by the Dyna-Drill Company.)

The possibility of buckling the BQ drill pipe is of continuous concern during the drilling operation. During reentry of the drill string into the pilot hole, rotary drilling and especially during Dyna-Drilling, the operator must be alert to possible buckling of the drill pipe. See Appendix G for further discussion of buckling.

The use of axial force without rotation increases the possibility that the bit may hang up on an obstacle instead of deflecting around. During the fast reentry (30 ft (9.2 in.) in 1 to 2 minutes was common) or when the torque Dyna-Drill strikes an obstacle and stalls, the operator may have problems in stopping the carriage travel before the small movements needed for buckling occur. For these reasons an alert, skilled operator is required at the controls.

Changing soil conditions or various bit and Dyna-Drill problems may require that the drill string be removed from the pilot hole. During this time out of the hole the question of hole stability arises. Softer, less compact soil conditions require the out-of-the-hole time be kept to a minimum. Also, care must be taken so that removal of the drill string does not remove the supportive slurry and leave a void. Fresh and perhaps a heavier slurry may have to be pumped into the hole during removal of the drill string to prevent these voids.

During reentry, the bent housing and deflection pad must be aligned with the course of the drill hole to prevent side tracking and beginning a new hole (especially in soft materials). Reentry should be accomplished without pumping new slurry. This allows the operator to sense the reactions of the drill pipe to be sure of proper tracking along the open pilot hole. This alignment restriction results because the bore must follow a path with a constant radius of curvature. Truly horizontal boring is restricted unless an in-hole, changeable angle bent sub or housing (as opposed to the fixed bent housing and deflection shoe now used for Dyna-Drilling) is employed to eccentrically couple the Dyna-Drill to the drill string.

WASHOVER

The washover operation is basically rotary drilling of drill or casting pipe. As shown in Figure N.5, slurry carries away all cuttings by feeding clean pressurized slurry down the center of the drill pipe across the washover bit and back out the entrance of the hole on the outside of the washover pipe. The pilot drill string or an already in place washover is used to guide the new larger washover.

The washover being advanced is attached to the drill head on the drill rig using an adapter. The operator rotates the washover at speeds of approximately 35 rpm. He advances the drill pipe according to the feel of the machine and tries to maintain a constant flow of "used" slurry out of the entrance to the hole. The feel of the machine indicates the horsepower demands required to advance and rotate the drill pipe. The constant flow of slurry indicates that the bit is not clogged and a sufficient amount of slurry is flowing to remove the cuttings. When horsepower demands increase and/or slurry flow decreases, the operator stops all forward movements while continuing rotation until slurry flow and horsepower demands return to normal.

Hydraulic fracture may occur during this operation. For a detailed analysis of the fracture potential of soils, see Appendix F.

LABOR DEPLOYMENT

Once the pilot hole drilling is started, barring any unforeseen problems, the essential operations of adding or removing drill pipe and taking surveys becomes routine. Four laborers in addition to the operator, supervisor, and directional engineer are required for constant operation. One laborer (chuck tender) is stationed on the machine carriage near the operator. His function is to handle the upper end of the drill pipe and the survey barrel. He also guides and supervises the connection of the drill head drive sub into the upper end of the drill pipe.

A second and third laborer are stationed at the lower end of the rig's frame to handle the lower end of the drill pipe and survey barrel. They use a drill pipe vise (shown in Figure N.11) and pipe wrenches for connecting the lower end of the drill pipe. These connections are always made by hand to eliminate the possibility of overtightening and stripping of threads if attached by the machine. Any free time while waiting for the drilling operation is used to wash the spilled bentonite slurry off the rig.

The fourth laborer (mud mixer) is mainly responsible for the slurry mixing operation. He must maintain the mud's viscosity at a minimum level to hold the pilot hole open and carry away the cuttings. The level of slurry in the tank is maintained by adding the required amounts of bentonite and water. He is also responsible for maintenance of desanding units required for recirculation units. For complicated drilling the fourth laborer should be replaced by a mud engineer.

Table N.1 presents example time periods required to complete the survey sequence ("Photograph" includes the time required to send the survey barrel down, take a picture, and retrieve; "Interpretation" includes the time required to develop the photograph) and the drill time required for each advance. The drilling times are variable depending on the type of soil and the drilling method. These examples are from conditions of poor drilling which forced Titan to move.

TABLE N.1: EXAMPLE TIMES FOR THE 30-FOOT DRILLING-SURVEY CYCLE
(Conditions forced reposition of equipment.)

Date	Penetration (ft)	Survey Time: Photograph (min)	Survey Time: Interpretation (min)	Drilling Time (min)	Notes
1/8	58	28	15	2	Rotary Drill
1/8	88	15	15	2	" "
1/8	118	10	--	2	" "
1/9	179	8	--	17	Dyna-Drill
1/9	179	8	60	60	" " ----------ream
1/10	209	9.5	12	--	" "
1/10	239	10	--	20	" "
1/10	269	10	--	30	" "
1/10	299	10	--	20	" "
1/11	329	11	--	60	Dyna-Drill--gravel
1/12	345	12	--	90	Rotary Drill--gravel
1/12	359	--	--	13	" " "
1/12	359	--	--	13	Rotary Drill--gravel--ream
1/12	359	--	--	32	" " " "
1/13	389	--	--	24	" " " "
1/13	404	--	--	36	" " " "
1/13	---	--	--	--	Drill rig down for transmission repair

(1 ft. = 0.305 m)

APPENDIX O

OPERATING COSTS OF MANDREL AND THRUSTER SYSTEMS

O.1 INTRODUCTION

At present these systems have only penetrated horizontal distances of 1000 to 2000 ft (300-600 m). Costs are based upon the experience and bids of two firms employing this technology: Titan Contractors (mandrel) and CONOCO (thruster).

Future market conditions assume a single active firm with variable length single contracts (2000-20,000 ft or 600 to 6000 m). Penetration distances per set up vary from 1500 to 3000 ft (460-900 m) for the mandrel system and 2000 to 20,000 ft (600 to 6000 m) for the thruster system. Since those distances represent an increase over past experience, the calculations are extrapolations.

The appendix is divided into a section for each basic system. Each section contains the assumptions and cost data necessary for the calculation. In addition, the total footage of drilling implicitly necessary to maintain the assumed market conditions is calculated to compare with anticipated future needs.

O.2 MANDREL SYSTEM

The operating and cost characteristics of the mandrel system are based upon the system developed by Titan Contractors. Actual data was acquired by (1) studying in detail Titan's activities during the 1200 ft (366 m) Cerritos Channel bore (See Appendix N), (2) analyzing their bid to the U. S. Navy for a 4000 ft (1220 m) bore in Hawaii, and (3) checking our analyses with Titan's own cost estimates for the 1680 ft (512 m) Wax Lake bore in Louisiana. Four Titan configurations (or potential configurations) were analyzed and graphed on a job length versus cost per foot basis. The assumptions for these analyses were as follows:

1) There would be enough soft ground tunnel exploration for the next seven years to keep a single Titan-like company as busy as the technology would permit.

2) The excavating subsystem has a useful life of seven years.

3) Work is performed 40 weeks per year, 6 days per week, 10 hours per day.

4) Mobilization and demobilization require 2 weeks total for each job irrespective of job length.

5) The soil conditions are encountered for the first time.

6) Basic costs are as follows:

   a. Equipment cost--$300,000 total

   b. Maintenance cost--$30,000 per year

   c. Insurance, Taxes, Interest--13% of equipment cost per year or $39,000 per year.

   d. Operating labor--$92 per hour

   e. Machinery rental--$14,560 per month

   f. Mobilization and demobilization labor--$106 per hour

   g. Accommodations, food, cars, supplies, etc.--$350 per day

   h. Slurry--$1.25 per foot

   i. Transport of rig--$8550 per week

   j. Miscellaneous costs--$1000 per week throughout entire job

   k. Indirect costs--50% of basic costs

The advance rate includes the subjective estimate of typical drill string trip time for drill bit replacement, deflection shoe change, and other wear-type adjustments.

The four configurations are defined as:

1. OLD Optimal: Drill 2 ft per minute (.6 m/min), stop for 3/4 hr to survey every 30 ft (9.2 m) for first 500 ft (152 m) and every 60 ft (8.3 m) thereafter, stop every 30 ft (9.2 m) for 1/2 hr for tool adjustment, stop for 2 days every 1500 ft (458 m) to move equipment.

2. OLD Bid: Actual drill time was subjectively estimated by contractor to be twice the drill time of OLD optimal resulting from contingencies, i.e. loss of lubricity while stopped.

3. NEW Optimal: Drill 2 ft per minute (.6 m/min), stop for 50 min every 300 ft (92 m) for drill string adjustment. Stop for 2 days every 3000 ft (915 m) to move equipment.

4. NEW Bid: Actual drill time will be assumed to be 1.5 times the drill time of NEW Optimal due to occasional loss of lubricity and unforeseen problems.

These four configurations differ then as follows:

1. The OLD configurations are based upon Titan's current drilling methods with the OLD Optimal being that method which has virtually no problem starting up again after stopping for survey or rod adjustments. The OLD optimal could correspond to drilling in stiff soils, such as

overconsolidated clay, and the OLD bid could correspond to drilling in something like silty sand.

2. The NEW configurations assume improvements in mud technology and continuous navigation have been applied to the OLD technology. This results in no survey stops, and lower probability of start-up failure (i.e. loss of lubricity) when stopped for drill string adjustment. New technology also results in additional equipment (navigation) rented for the system and two additional people (a navigation and a mud specialist) added to the labor crew at an increased labor cost of $30 per hour. The navigation equipment costs are based on Scientific Drilling Controls Eye System.

Costs were computed for seven different average job lengths for each of the four configurations and plotted in Figure 0.1. The job length represents the total drilling length in one locality. Even though the old configurations will have difficulty penetrating further than 1500 ft (458 m), the costs will be lower if contracts are let for longer lengths in one city. This savings results from decreased transporation, mobilization, and "learning" costs.

As stated above, it was assumed that all jobs of a given category were the same length, i.e. the cost for OLD-optimal at 5000 ft (1525 m) assumes 7 years of 5000-ft (1525 m) jobs by a single contractor. This assumption has implications for the total amount of exploration in 7 years by each alternative and on the assumed market for such exploration. This implicit variation in work is illustrated in Table 0.1 which shows the total number of jobs and footage which must be penetrated in 7 years for the stated costs to hold true for a single company market for 3 typical job lengths (2000, 10,000, and 20,000 ft/ 610, 3050, and 16,000 m) for each of the four configurations.

0.3 THRUSTER SYSTEM

Three thruster configurations were analyzed for cost:

Thruster A--Electric motor, thrust applicator, 7 in. (17.8 cm) hole.

Thruster B--Mud hydraulic motor, thrust applicator, 7 in. (17.8 cm) hole.

Thruster C--6 3/4 in. (17.2 cm) Dyna-Drill, thrust applicator, 12 in. (30.5 cm) hole.

Thrusters A, B, and C differ little cost-wise, and hence only figures for A appear below. The cost difference is $30 per day less for B than A.

Since configurations of this type have not been field tested, the cost figures are estimates and approximations and therefore are not refined as the preceding figures for the mandrel system. However, a similar system has been employed by CONOCO to excavate 800 ft (244 m) holes in soft coal. Their experience and costs--as much as they were willing to divulge--have been incorporated into the following cost estimate.

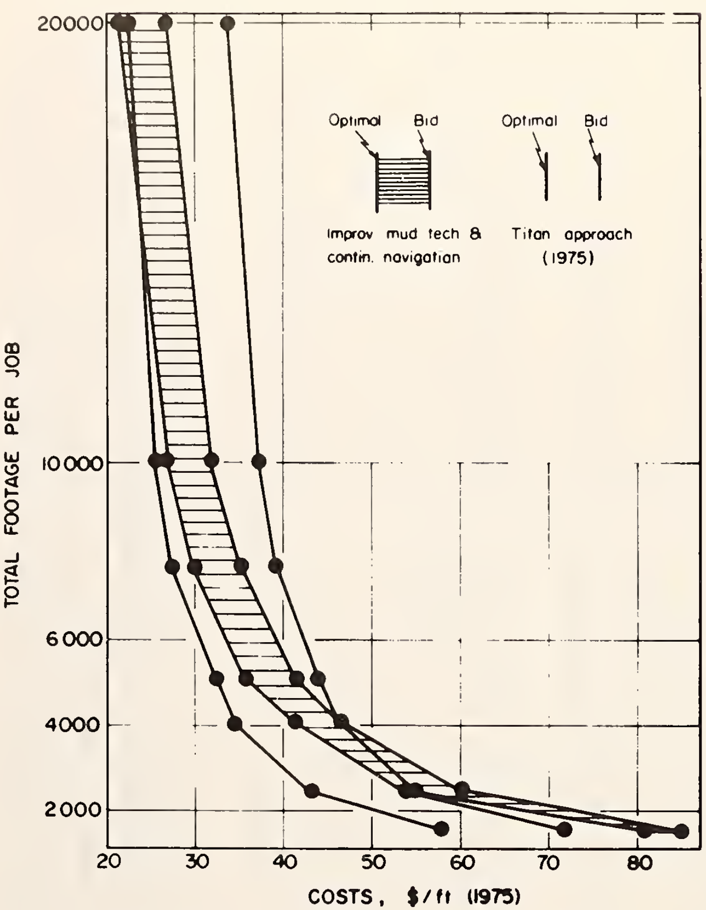


FIGURE 0.1 MANDREL PENETRATION COSTS
INCL.
DRILLING CONDITIONS, TECHNOLOGY IMPROVEMENT & MARKET CONDITIONS

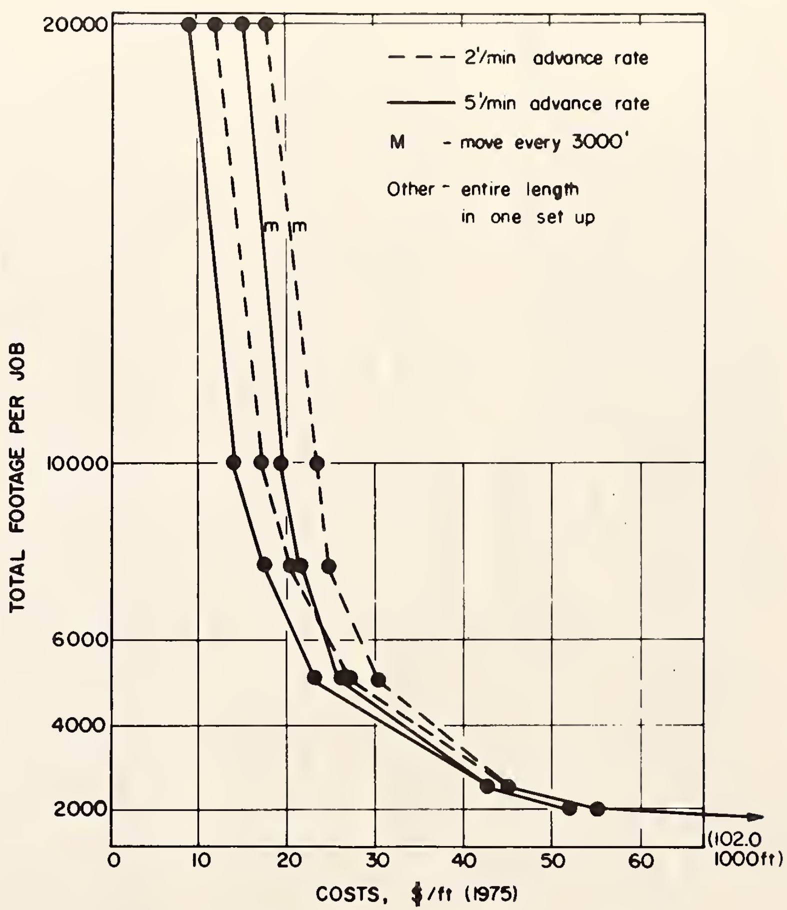


FIGURE 0.2 THRUSTER PENETRATION COSTS
INCL.
DRILLING CONDITIONS, TECHNOLOGY IMPROVEMENT & MARKET CONDITIONS

(1 ft. = 0.305 m)

TABLE 0.1: MARKETS IMPLICIT IN COST ANALYSIS
FOR MANDREL SYSTEM

Length/Job and Configuration	Total Days Per Job	Total Jobs Per Year	Total Jobs Per 7 Years	Total Feet Explored—7 Years
2000 ft length				
OLD-Bid	32	7 1/2	52 1/2	105,000
-Optimal	23	10 1/2	73	146,000
NEW-Bid	18	13 1/2	93 1/3	187,000
-Optimal	16	15	105	210,000
10,000 ft length				
OLD-Bid	102	2 2/5	16 1/2	165,000
-Optimal	63	3 4/5	26 2/3	267,000
NEW-Bid	44	5 1/2	38 1/5	382,000
-Optimal	35	6 6/7	48	480,000
20,000 ft length				
OLD-Bid	190	1 1/4	8 9/10	177,000
-Optimal	114	2 7/10	14 3/4	295,000
NEW-Bid	75	3 1/5	22 2/5	448,000
-Optimal	58	4 1/7	29	579,000

(1 ft. = 0.305 m)

The following assumptions were made for the thruster cost analysis:

1. Transport costs are the same as for Titan.
2. Labor charges per day are the same as Titan's NEW configuration.
3. Miscellaneous costs are the same as for Titan.
4. Slurry costs are the same as for Titan.
5. A deflection shoe costs $2,000 and has a life of 100 hours in-hole time.
6. Orienting motor costs $3,000 and has an in-hole life of 100 hours.
7. Bit life is 100 hours. The bit for Thruster A costs $1,800; for Thruster C, $3,500.
8. Mobilization and demobilization take 2 weeks total per job.
9. Crews work 6 days per week, 10 hours per day, 40 weeks per year.
10. The thruster drills at rates of 5 and 2 ft (1.5 and 0.6 m) per minute.
11. The thruster is cabled and hence has no stops for surveying.
12. Scientific Control's "Eye" continuous navigation system is included as part of the thruster system.
13. Equipment costs include the drill, the motor, the basic thruster, hydraulic power unit, hose handling equipment, hoses and pumps, navigation equipment, but do not include surface equipment other than hose handling.
14. Interfacing costs are itemized separately and pertain to the costs involved in putting the components together and testing these interfaced components as a system. These are those interface costs related to production rather than to development and hence are included here.
15. An indirect charge of 50% has been applied, the same as for Titan.
16. A life of 2 years was assumed for the thrust applicator.

The major differences, therefore, between Titan costs and thruster costs are:

a. Differences in the costs of the hardware components ($46,000 for Thruster A; $83,000 for Thruster C; and $300,000 for Mandrel 1).
b. Differences in the time to drill a given length job. thruster needs no stops for survey or drill string adjustment while mandrel must stop at least for drill string adjustment.

The thruster costs are presented in Tables 0.2 and 0.3 for configuration A with advance rates of 2-5 ft/min (.6-1.5 m/min) for six different job lengths. These costs assume that once drilling starts it continues until the job length is reached, irrespective of job length. Table 0.4

TABLE 0.2: DETAILED COSTS FOR THRUSTER A

(Mobilization/Demobilization Time=12 Days, Advance Rate=2 ft/min)

Job Length

Cost Component	2000 ft 610 m	2500 ft 762 m	5000 ft 1525 m	7500 ft 2288 m	10,000 ft 3050 m	20,000 ft 6100 m
Mobil/Demobil--Labor, Room	16,920	16,920	16,920	16,920	16,920	16,920
Electric Motor	1,358	1,358	1,649	1,843	2,037	2,813
Bit	306	378	756	1,134	1,512	3,006
Deflection Shoe	340	420	840	1,260	1,680	3,340
Orienting Motor	510	630	1,260	1,890	2,520	5,010
Transport	17,100	17,100	17,100	17,100	17,100	17,100
Miscellaneous	2,334	2,334	2,834	3,167	3,500	4,834
Thruster	1,374	1,374	1,668	1,868	2,123	2,919
Drilling Labor, Room	2,540	2,540	6,350	8,890	11,430	21,590
Slurry	2,500	3,125	6,250	9,375	12,500	25,000
Navigation Rental	23,602	23,602	28,660	32,032	35,403	48,890
Navigation and Mud Labor	4,200	4,200	5,100	5,700	6,300	8,700
Maintenance (10%)	137	137	167	187	212	292
Insurance, Taxes, Etc. (13%)	179	179	217	243	276	379
Interface (50%)	687	687	834	934	1,062	1,460
Subtotal	74,087	74,984	90,605	102,543	114,575	162,253
Indirect (50%)	37,044	37,492	45,303	51,272	57,288	81,127
TOTAL	111,131	112,476	135,908	53,815	171,863	243,380
Per Foot	55.57	44.99	27.18	20.51	17.19	12.17

(1 ft. = 0.305 m)

TABLE 0.3: DETAILED COSTS FOR THRUSTER A

(Mobilization/Demobilization Time=12 Days, Advance Rate=5 ft/min)

Cost Component	Job Length and Drill Time: 1 day 2000 ft 610 m	1 day 2500 ft 762 m	2 days 5000 ft 1525 m	3 days 7500 ft 2288 m	4 days 10,000 ft 3050 m	7 days 20,000 ft 6100 m
Mobil/Demobil-- Labor, Room	16,920	16,920	16,920	16,920	16,920	16,920
Electric Motor	1,261	1,261	1,358	1,455	1,552	1,843
Bit	126	162	306	450	612	1,206
Deflection Shoe	140	180	340	500	680	1,340
Orienting Motor	210	270	510	750	1,020	2,010
Transport	17,100	17,100	17,100	17,100	17,100	17,100
Miscellaneous	2,167	2,167	2,333	2,500	2,667	3,167
Thruster	1,262	1,262	1,374	1,459	1,557	1,868
Drilling Labor, Room	1,270	1,270	2,540	3,810	5,080	8,890
Slurry	2,500	3,125	6,250	9,375	12,500	25,000
Navigation Rental	21,916	21,916	23,602	25,288	26,973	32,031
Navigation and Mud Labor	3,900	3,900	4,200	4,500	4,800	5,700
Maintenance (10%)	126	126	137	146	156	187
Insurance, Taxes, Etc. (13%)	164	164	179	190	202	243
Interface (50%)	631	631	687	730	779	934
Subtotal	69,693	70,454	77,836	85,173	92,598	118,439
Indirect (50%)	34,847	35,227	38,918	42,587	46,299	59,220
TOTAL	104,540	105,681	116,754	127,760	138,897	177,659
Per Foot	52.27	42.27	23.35	17.03	13.89	8.88

(1 ft. = 0.305 m)

TABLE 0.4: THRUSTER COSTS WITH A MOVE EVERY 3000 FT

Job Length

	2000 ft 610 m	2500 ft 762 m	5000 ft 1525 m	7500 ft 2288 m	10,000 ft 3050 m	20,000 ft 6100 m
Thruster A, 5 ft/min						
No Move Cost	104,540	105,681	116,754	127,760	138,897	177,659
Move Cost	0	0	16,679	34,069	52,086	112,206
TOTAL	104,540	105,681	133,433	161,829	190,983	289,865
Per Foot	52.27	42.27	26.69	21.58	19.10	14.49
Thruster A, 2 ft/min						
No Move Cost	111,131	112,476	135,908	153,815	171,863	243,380
Move Cost	0	0	15,989	32,382	49,104	100,709
TOTAL	111,131	112,476	151,897	186,197	220,967	344,089
Per Foot	55.57	44.99	30.38	24.83	22.10	17.20

(1 ft. = 0.305 m)

presents revised costs, assuming that the equipment must be moved every 3000 ft (915 m) and that such a move takes 2 days. These tables are combined graphically in Figure 0.2.

Since the thruster is written off over its life of two years, Table 0.5 shows the available job and drilling footage implications and total explored miles necessary for the above costs to hold for a single company.

TABLE 0.5: MARKETS IMPLICIT IN COST ANALYSIS FOR THRUSTER SYSTEM

Length/Job and Configuration	Total Days Per Job	Total Jobs Per Year	Total Jobs Per 7 Years	Total Feet Explored-- 7 Years
2000 ft length				
No Move				
5 ft/min	13	18 1/2	129 1/2	259,000
2 ft/min	14	17 1/2	122 1/2	240,000
Move every 3000 ft				
5 ft/min	13	18 1/2	129 1/2	259,000
2 ft/min	14	17 1/2	122 1/2	240,000
5000 ft length				
No Move				
5 ft/min	14	17 1/2	122 1/2	600,000
2 ft/min	17	14	98	495,000
Move every 3000 ft				
5 ft/min	16	15	105	525,000
2 ft/min	19	12 2/3	88 2/3	441,000
10,000 ft length				
No Move				
5 ft/min	16	15	105	1,050,000
2 ft/min	21	11 1/2	80 1/2	801,500
Move every 3000 ft				
5 ft/min	22	11	77	763,000
2 ft/min	27	9	63	623,000

(1 ft. = 0.305 m)

APPENDIX P

A VALUE ANALYSIS OF ALTERNATIVE EXPLORATION METHODS

P.1 SCENARIO APPROACH

A scenario approach was adopted to determine the "best" method for exploration of a given geology. Simplification to scenarios was necessary for two main reasons: First, only hypothetical probabilities of instance of a condition are available for a non site-specific study. Secondly, as discussed in Appendix J concerning geophysical exploration, a comparative assessment of the reliability of different exploration methods is nearly impossible because of the interpretational nature of geophysical exploration. Thus, for the scenarios it was assumed that given unanticipated conditions did exist (probability = 1) and that the reliability of the exploration methods could be subjectively assessed.

As an alternative, the value analysis procedure outlined in "Improved Subsurface Investigation for Highway Tunnel Design and Construction" (Ash et al, 1974) was investigated for adoption. As discussed above, comparative evaluations of site-specific conditions and reliabilities are not available and would require additional investigation. Therefore, Ash's approach was simplified to the scenario level.

There is a scenario for two principal unanticipated conditions--running ground and boulder obstruction. Each scenario includes a marginal tunneling cost estimate of an unanticipated condition (MV) which is a function of exploration approach. The marginal costs, discussed in Section 4.3, are the "values" of subsurface exploration as they could be eliminated by extensive investigation. Each scenario will also include marginal exploration cost estimates MC. These marginal costs are separated into two groups, exploration from the surface--discussed in Section 4.4, and horizontal exploration--discussed in Section 4.5.

Ratios of MV/MC for each scenario will be compared for alternative exploration methods and two tunnel invert depths, 75 ft (23 m) and 150 ft (46 m). By comparing these ratios, the "best" method for exploring for a specific unanticipated condition--scenario--can be found as a function of the tunnel depth.

The following modes of exploration will be compared:

(1) Vertical borings @ the following intervals:

a. 300 ft (91 m)
b. 100 ft (30 m)
c. 50 ft (15 m)

(2) Vertical boring at 50 ft (15 m) intervals plus cone penetrations at 10 ft (3 m) intervals

(3) Surface refraction studies (reflection with sufficient resolution is impossible with present technology)

(4) Horizontal boring and on-board geophysical sensing (thruster only)

(5) Horizontal boring and a following geophysical package

a. Thruster
b. Mandrel

The costs are found from an examination of the following figures and tables. These are OPERATIONAL costs in terms of 1974 dollars.

Exploration Method	Table (T)/Figure (F)
1a	
b	F 4.5
c	
2	F 4.5
3	T 4.3
4a	F 4.1 and T 4.6
5a	F 4.7 and T 4.6
b	F 4.6 and T 4.6

The assumptions pertaining to the origin of the cost data are discussed where the figures and tables are presented.

Costs of exploration from horizontal holes requires further explanation to account for on-board and follower sensing. Costs projected include continuous navigation equipment and personnel for both thruster and mandrel. Since simultaneous sensing and exploration will require slower penetration rates, 2 ft/min (.6 m/min), operational costs will be employed for the thruster systems. Interfacing of sensing and excavation equipment for exploration method 4 is not likely to cost more than \$10 to \$15/ft (\$32 to \$40/m). On-board operational sensing costs are estimated to be the same as the operational costs for follower packages.

The following example will illustrate the interfacing costs for one exploration subsystem. Suppose it will cost \$100,000 to wed the piezometer cone to the excavation system. If the \$100,000 is amortized over the next 7 years, the present worth is \$150,000. If this system were employed to explore 50,000 ft (15,250 m)--only 1/9 of the expected soft ground transportation market--over the next 7 years, the cost would be \$3/ft (\$10/m).

The values of exploration (MV) are assigned for each exploration method based upon its reliability. The reliability of the exploration method is the inverse of the adversity of unexpected conditions (low,

medium, and high in Figure 4.3). In other words a more reliable method will result in fewer adverse unexpected conditions. A highly reliable method will result in conditions of low adversity and MV is cost at high adversity minus BEC. A method with a medium reliability will have conditions of medium adversity and MV is cost at high adversity minus cost at medium adversity.

The estimates of reliability and adversity are subjective. However, these estimates have not been made in the absence of experience. The Washington case indicates that even with borings spaced at 50 ft (15 m) intervals, unexpected boulders can still be encountered.

These estimates of reliability and adversity need further refinement and additional research but do not invalidate the dollar costs/value presented in Figure 4.3. The reader is encouraged to substitute his own subjective estimates of reliability. These substitutions will effect MV on the MV/MC tables for the two scenarios.

P.2 BOULDERS

Assumed subsurface conditions for exploration for boulders shown in Figure P.1 are as follows:

1. Boulders are 5 to 10 ft (1.5 to 3 m) in diameter
2. Tunnel depth is 75 to 150 ft (23 to 56 m)
3. Tunnel length is 5000 ft (1525 m)
4. Groundwater table is at 10 ft (3 m) below the surface
5. Soil is residual

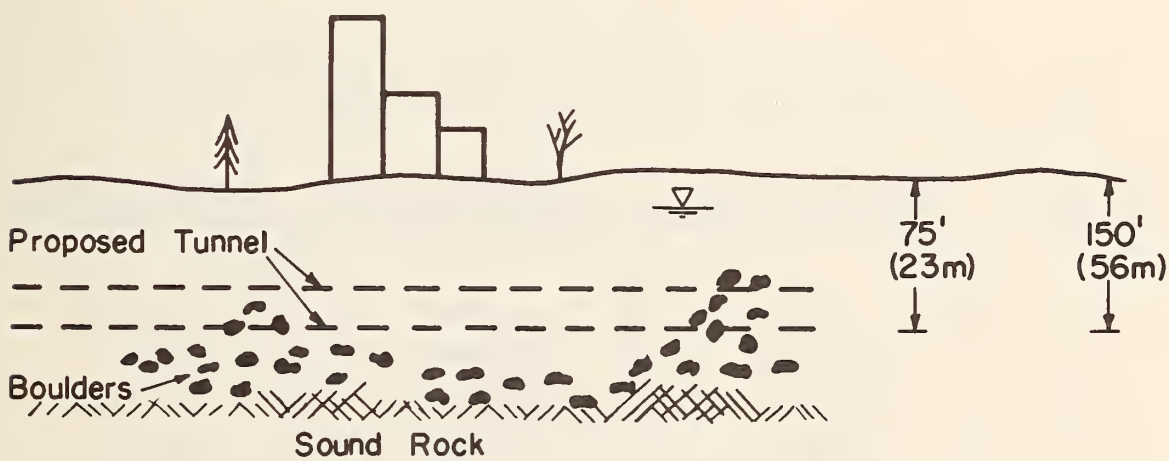


FIGURE P.1 EXPLORATION FOR BOULDERS: GEOMETRY

The value of knowing the locations of the boulders is estimated from Figure 4.3. It is the additional construction cost (MV) associated with working around unexpected boulders, many times by hand. The MV is the cost of mining with the presence of boulders minus the basic excavation cost (LEC) and ranges from \$0 to \$500/ft (\$0 to \$1600/m). MV's for each exploration method are assigned in Table P.1.

Costs (MC) were assigned as described in the Common Background section with the following additional assumptions:

(1) Boulders are best found during horizontal penetration by geophysical means and direct contact. Therefore cone piezometer and additional following package costs are not considered.

(2) Geophysics costs per foot were multiplied by 10 to account for the extra length of lines necessary to isolate locations.

(3) The horizontal boring costs were calculated assuming that each system could penetrate 2000 ft (600 m) and that boring not located in the tunnel outline increased the costs. See Figure G.14 for distances and depths to horizontality.

(4) Exploration costs for the follower were estimated from the geophysics case study presented in Section 4.5.

(5) Exploration costs for on-board sensing are those associated with a follower plus the interface costs for the geophysics package.

TABLE P.1: MARGINAL VALUE OF EXPLORING FOR UNEXPECTED BOULDERS

Exploration Method	Relative Value of Exploration Results	Adversity of Unexpected Condition	Marginal Value of Exploration Data
1 a	low	high	0
b	low-medium	high-medium	\$125/ft
c	medium	medium	\$250/ft
2	high	low	\$350/ft
3	low-medium	high-medium	\$0/ft
4	high	low	\$500/ft
5	high	low	\$500/ft

(1 ft. = 0.305 m)

Results of the economics of boulder location under the above described conditions are given in Table P.2. The comparison indicates the following:

(1) Any exploration with borings spaced less than every 300 ft (92 m) is beneficial (provided the boulders are equally likely along the section).

(2) Horizontal boring becomes the most cost effective method of excavation only for tunnel depths greater than 75 to 100 ft (23 to 30 m) deep.

(3) Mandrel costs are only marginally more expensive than those associated with the thruster.

(4) Benefits of surface geophysical exploration are unexpectedly high. This results because (1) the costs of confirmation boreholes are not included and (2) the MV was difficult to assess.

TABLE P.2: EXPLORATION FOR BOULDERS

Marginal Value ($/ft)/Marginal Cost ($/ft)

Exploration Method	Depth of Invert 75 ft (23 m)		150 ft (56 m)	
1. Vertical Borings				
300 ft	0/3	0	0/8	0
100 ft	125/19	6	125/31	4
50 ft	250/28	9	250/50	5
2. Vertical Borings & Cone Penetration	350/71	5	350/152	2
3. Surface Refraction	0/15	0	0/15	0
4. Horizontal Boring & On-Board Sensing	500/62	8	500/67	7
5. Horizontal Boring & Follower--Thruster	500/59	8	500/63	8
Mandrel	500/68	7	500/73	7

(1 ft. = 0.305 m)

P.3 RUNNING SAND LENSES

Assumed subsurface conditions for exploration for sand lenses shown in Figure P.2 are as follows:

1. The sand lenses are 15 ft (4.5 m) thick
2. Tunnel depth is 75 - 150 ft (23 - 56 m)
3. Tunnel length is 5000 ft (1525 m)
4. Groundwater table is at 10 ft (3 m) below the surface
5. Soil is glacial fluvial.

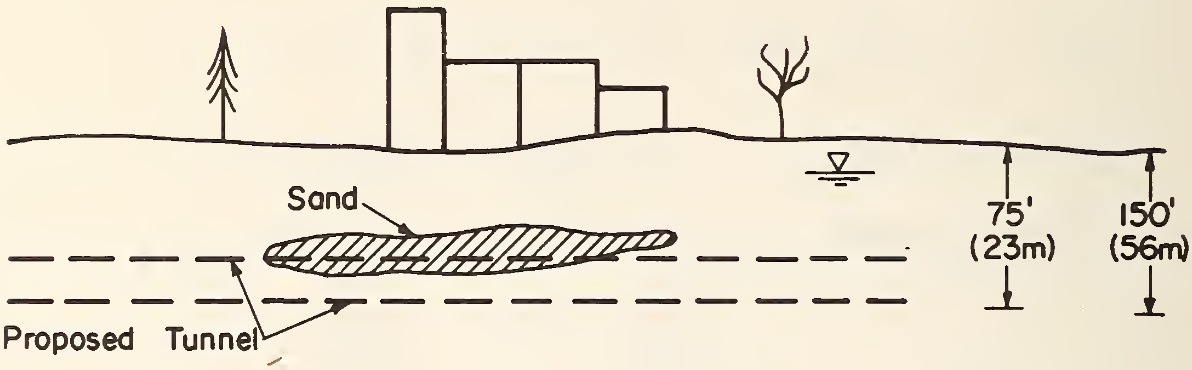


FIGURE P.2 EXPLORATION FOR RUNNING SAND: GEOMETRY

The value of knowing the existence of running ground is estimated from Figure 4.3. It is the additional construction cost (MV) of possible hand excavation by breast board or compressed air. The MV is therefore the cost of mining under adverse hydrogeological conditions minus the BEC and can be as high as $1100/ft ($3605/m). MV's for each exploration method are assigned in Table P.3.

Costs were assigned as described in the background section with the following assumptions:

(1) Running ground can best be detected with the piezometer cone. Therefore the surface cone penetration will have to be made with the cone piezometer. Therefore the number of vertical holes might double and costs of holes at 50 were multiplied by 2.

(2) Geophysics costs are irrelevant because of the low value of the information with regard to running ground (at the present state of art).

(3) Horizontal boring costs were calculated assuming that each system could penetrate 2000 ft (600 m) and that boring not located in the tunnel outline increased costs. See Figure G.14 for distances and depths to horizontality.

(4) Exploration costs for on-board sensing are the same as those determined for boulders plus the costs associated with interfacing the cone piezometer.

(5) Exploration cost for a follower caliper study to measure collapse upon lowering of mud pressure could cost $1000/day. Therefore its costs would be approximately $5/ft.

TABLE P.3: MARGINAL VALUE OF EXPLORING FOR UNEXPECTED RUNNING SAND

Exploration Method	Relative Value of Exploration Results	Adversity of Unexpected Condition	Marginal Value of Exploration Data
1 a	low	high	0
b	low	high	0
c	medium	medium	$800/ft
2	NO ADVANTAGE OVER 1C		
3	low	high	0
4	medium	medium	$800/ft
5	high	low	$800/ft

(1 ft. = 0.305 m)

Results of the economics of sand lense location under the above described conditions and assumptions are given in Table P.4. The analysis indicates the following:

(1) Again any extended exploration is beneficial (provided the running sand lenses are equally likely along the route).

(2) Since the costs of exploration for running ground do not increase proportionally to the value, the ratios of MV/MC are greater for unanticipated running sand (ground) than unanticipated boulders.

TABLE P.4: EXPLORATION FOR RUNNING SAND LENSES

Marginal Value/Marginal Cost

Exploration Method	Depth of Interest 75 ft (23 m)		150 ft (56 m)	
1. Vertical Borings				
300 ft	0/-		0/-	
100 ft	0/-		0/	
50 ft	800/56	14	800/100	8
2. Vertical Borings & Cone Penetration	800/71	11	800/152	5
3. Surface Refraction	0/-		0/-	
4. Horizontal Boring & On-Board Sensing	800/62*	13*	800/67	12
5. Horizontal Boring & Follower--Thruster	800/59*	14*	800/63	12
--Mandrel	800/68*	12*	800/73	11

(1 ft. = 0.305 m)

* Hydraulic facture may occur in loose sands which may prevent successful horizontal penetration.

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FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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